



PHD

Industrial energy efficiency: Interdisciplinary perspectives on the thermodynamic, technical and economic constraints

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Award date:
2009

Awarding institution:
University of Bath

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A1 Publications

A1.1 Energy Policy paper based on OSI State of Science Review on Enabling Technologies for Industrial Demand Management

Dyer, C. H., Hammond, G. P., Jones, C. I., & McKenna, R. C., 2008, "Enabling technologies for industrial energy management", *Energy Policy*, vol. 36, pp. 4434-4443. [doi:10.1016/j.enpol.2008.09.028](https://doi.org/10.1016/j.enpol.2008.09.028) (Due to copyright restrictions this journal paper cannot be reproduced here in the electronic version of this thesis.)

A1.2 Solicited reproduction of conference paper from the International Conference of the Society for Sustainability and Environmental Engineering, Perth, Australia, November 2007

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The Environmental Engineer is sent to all
members of the SSEE four times a year. It
is also available via subscription. Journal
subscription fees for 2008 are as follows:

Member	\$30
Non-Member	\$40
O/S Member	\$35
O/S Non-Member	\$45

ENGINEERING SUSTAINABILITY: ENERGY EFFICIENCY, THERMODYNAMIC ANALYSIS AND THE INDUSTRIAL SECTOR

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Keywords: Energy efficiency, industry, barriers, drivers, exergy.

Abstract

The UK's transition to a low-carbon economy is underpinned by the government's aspiration to reduce carbon dioxide (CO₂) emissions by 60% on 1990 levels by 2050. The industrial sector currently accounts for around one third of indigenous CO₂ emissions and is therefore the focus of much work aimed at mitigation towards meeting this target. The present contribution examines the drivers and barriers to the uptake of industrial efficiency measures, before discussing the issues involved in measuring industrial efficiency and finally considers thermodynamic methods of analysis. Significant differences can be found between the energetic and exergetic efficiencies of devices and macroeconomic systems. In practice, though, the so-called exergetic improvement potential is always limited by technical and economic constraints.

1. Introduction to UK Industry

The industrial sector in the UK consistently contributes around 10% of the GDP and thereby supports the large growth in the tertiary sector (ONS 2006). It accounts for some 21% of total delivered energy and 29% of carbon

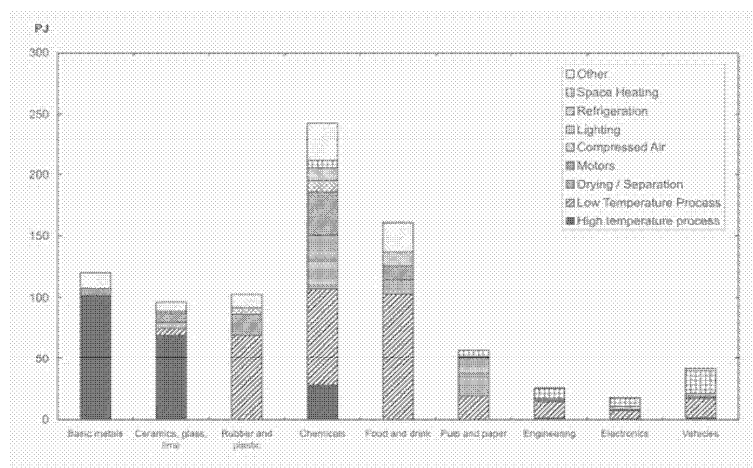


Figure 1. Industrial energy consumption by end use and sector in 2004 (DTI 2004).

emissions (ONS 2006; DTI 2007). However, it is the only sector to have undergone a significant fall of roughly 40% in final energy demand since the early seventies, in spite of an increase in the value of output of over 40% in real terms during this period.

The overall reduction in energy intensity (in units TJ/£million of gross value added, GVA) masks different underlying

causes. These include massive improvements in energy efficiency, accounting for an estimated 80% of the fall in industrial energy consumption between 1965 and 1995 (DTI 2002, p.32). Structural change within the UK accounts for most of the remaining 20% reduction in industrial energy intensity, with a general move away from so-called heavy industries (DTI 2002, pp.33–34). Fuel switching has also

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contributed to a much ‘cleaner’ industrial sector, as coal and oil use has steadily declined in favour of natural gas. Despite considerable improvements in energy efficiency over the past few decades, significant thermodynamic potential still remains (Hammond & Stapleton 2001).

Figure 1 shows the large difference between subsectors in terms of end-use applications. Much diversity can be found throughout industry, especially in terms of products manufactured, processes undertaken and technologies employed, all of which determine energy use (Dyer *et al.* 2006).

Manufacturing processes range from highly energy-intensive steel production and petrochemicals processing to low energy-intensity electronics fabrication. Whereas the former typically employs large quantities of (often high-temperature) process energy, the latter tends to be dominated by energy uses associated with space heating.

The largest energy-consuming industrial subsectors in the UK, according to the Standard Industrial Classification (SIC; ONS 2003), are Iron and Steel, Chemicals, Food and Drink, and Rubber and Plastics. Together these sectors account for around half of industrial energy use. The subsectors with the largest value of output, in GVA, are those that generally undertake processing operations occurring late in the product’s ‘manufacturing phase’. These include the assembly of prefabricated components, especially in the Automotive and Mechanical Engineering subsectors, and operations that add much additional value to a product, such as Food and Drink manufacture and Printing and Publishing. At the other end of the GVA scale are sectors performing mainly primary processing operations, such as Basic Metals and Ceramics. Primary processing operations add relatively little added value in comparison to secondary and finishing operations occurring later in the product’s ‘manufacturing phase’.

2. Drivers and Barriers for Industrial Energy Efficiency

Drivers. The two primary drivers behind industrial uptake of energy efficiency are costs and legislation. Energy costs represent a large proportion of operating expenditure (often as much as half) for energy-intensive sectors, whereas for non-energy-intensive sectors they are an

order of magnitude smaller than this (up to 5%). Hence, this driver is much stronger within the energy-intensive sectors and has been recently emphasised by drastic increases in natural gas prices (DTI 2006a), upon which these industries are now heavily dependent.

Environmental legislation typically punishes firms for polluting, by imposing fiscal penalties on the burning of fossil fuels. The great majority of industrial legislation currently focuses on controlling CO₂ emissions. On a European scale, the EU Emissions Trading Scheme (EU ETS) is a ‘cap and trade’ policy, which aims to create a market for carbon. Phase I runs from 2005 to 2007, with the commencement of Phase II in 2008 until 2012. The allocation of permits to each sector is based on the projected emissions for that particular sector, but there remain some problems that need to be addressed. Specifically, the method for allocating the permits in Phase I has been criticised because some member states have proffered liberal estimates of their projected emissions in order to obtain more permits – most notable, perhaps, is Germany, which has admitted this to be the case. It has also been suggested that the total number of permits allocated was too high and that the frequency of information disclosure was too infrequent (Lewis 2006). The latter resulted in the market’s ignorance regarding the oversupply of permits, which meant it was trading on a false premise. The procedure for determining the national allocation plans (NAPs) for member states has been more stringent for Phase II and is anticipated to produce a more efficient market for carbon. The Department for Environment, Food and Rural Affairs (DEFRA), the government department that administers the Scheme, is currently undertaking a consultation regarding the introduction of auctioning rather than grandfathering (DEFRA 2008), which might be a partial solution to these problems associated with inefficient pricing.

Domestic policy for industry is concentrated in the Climate Change Levy (CCL), a tax on fuel for the heavy industries. Some sectors have negotiated Climate Change Agreements (CCAs), which involve a dispensation from the tax in return for undertaking energy-saving measures towards meeting specific targets. It has been independently estimated by Cambridge Econometrics that full carbon savings

from the CCL by 2020 will be of the order of 3.7 million tonnes of carbon (DEFRA 2006).

Additional drivers for energy efficiency include competitiveness within the marketplace, associated intangible benefits (such as corporate social responsibility) and fiscal support from third parties – such as the Carbon Trust – but these are usually secondary in industry (The Carbon Trust 2005). Firms should focus on the overall benefits of energy efficiency, however, because the associated benefits in other areas can also be significant (e.g., improvements in productivity; see Worrell *et al.* 2003). In fact, the non-energy benefits are often greater than the value of the direct energy savings (Pye & McKane 2000, cited in Sandberg 2004, p.18).

Barriers. The barriers to industrial energy efficiency are more varied than the drivers. They include, *inter alia*, economic market and non-market failures, the investment costs associated with new plant, and a certain degree of inertia. Perhaps the most significant non-market failures are those of hidden costs and access to capital, which have often been cited in the literature as reasons given (e.g., in energy audits) for not undertaking energy-efficiency measures. Of the market failures, imperfect information appears by far to be the strongest barrier. These two barriers were similarly recognised in the UK Government’s Energy Review in 2006 (DTI 2006b). Jaffe and Stavins (1994) also highlight some market failures associated with the public good of information, in particular its non-rival and non-excludable properties, which for energy-efficiency technologies is a significant barrier to uptake.

In addition, there are barriers such as the limited ‘window of opportunity’ for the installation and maintenance of new plant, the limited resources for this type of activity – which is particularly prevalent with small and medium sized enterprises (HM Treasury *et al.* 2005) – the lack of expertise resulting from a rationalisation of the workforce and a general reluctance to adapt to changing practices, which might often be associated with a certain degree of inertia (St John Cox & Future Energy Solutions 2005).

3. Defining and Measuring Industrial Efficiency

Definition. The term ‘energy efficiency’ is often used without being

defined, and when it is, the meaning of the term is very much dependent upon the context. The main reason for this discrepancy is that the term is applied to system boundaries with a broad range of sizes and scopes. Although energy efficiency has an important place on the public agenda of many countries, surprisingly little attention has been given to defining and measuring the term (Patterson 1996, p.386). Various definitions have been suggested, which are all very similar, yet are open to interpretation and still remain somewhat ambiguous (European Commission 2006, pp.27–28). The most common definition in industry is the energy consumed per unit of product or output, sometimes referred to as the specific energy consumption (SEC), or the energy intensity. Energy consumption is measured in joules, and output can be measured either in physical quantities (e.g., tonnes, number of items) or economic quantities (measured in gross domestic product (GDP) for a country or GVA on a subnational scale, in pounds or dollars). The following section will address some of the issues involved in selecting appropriate measurement indicators.

Measurement. The measurement of industrial energy intensity is ultimately determined by the way in which the output is defined. Economic measures of intensity are generally more widespread, which is largely because of their consistency in aggregation. An energy intensity in economic terms can be aggregated across sectors and compared through time periods, something that is not always possible with physical measures in very different units.

One of the main disadvantages of economic, or value-based, indicators is that they are inevitably based on price indicators for which the suitable selection process is problematic (Freeman *et al.* 1997). For most if not all goods and services, several prices exist, only one of which is the actual price at which the transaction occurs – the so-called transaction price. The price that is recorded for statistical purposes does not always correspond to the actual transaction price. A good example of this is in the trade of bricks for construction, where the price is negotiated between the supplier and the customer on a one-off basis.

The consequence of this is that *actual* changes in quantity of output can be

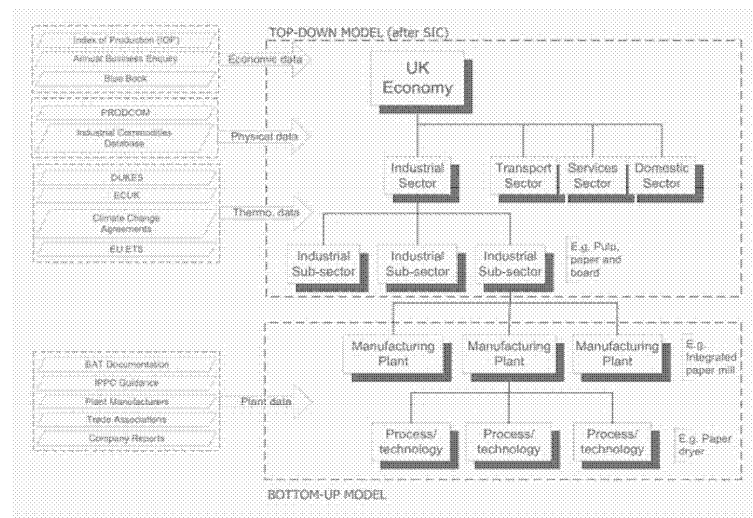


Figure 2. Integrated top-down and bottom-up model of the UK industrial sector.

overlooked and/or exaggerated. The latter would especially be the case when a sudden increase in demand results in a sudden 'price hike'. In economic terms, the *value* of output would have increased, but the quantity of output might well have remained constant or even reduced (Farla 2000, p.9). This problem is exacerbated for inelastic goods and services, for which changes in supply and demand do not significantly affect the market price. A good example is petroleum (and other crude oil derivatives), for which customers' demand is usually insensitive to fluctuations in the price, within a certain range (i.e., the elasticity is not absolutely zero).

In contrast, physical volume indicators provide a more realistic representation of industrial output. Their main limitation is the non-homogeneity of products produced within industrial subsectors. This means that it is often impossible to aggregate the output from a subsector because of the different physical units employed. More significantly, this means that output cannot properly be measured in physical terms. In fact, often the only way to measure output in non-homogenous subsectors is by value. Consider, for example, the microelectronics industry, which produces a vast array of outputs, for which a specific physical unit of output is not appropriate.

Furthermore, there are problems relating to the classification of both types (i.e., economic and physical) of

data. The international standard for classifying economic activity is the Standard Industrial Classification (SIC; see ONS 2003; updated for 2008, see ONS 2007). Changes in the correspondence between the classification itself and the industrial activity it represents can cause errors in the respective datasets. Firms are classified within SIC according to the majority of their output. In some cases, however, the majority of a firm's output is used internally (i.e., an intermediate product) or within the same industry (Freeman *et al.* 1997, p.712). This can also lead to double-counting, because this intermediate product is then further processed into the final output for the firm or subsector.

SIC-related errors can also result when a firm or industrial subsector changes its production mix sufficiently to warrant reclassification in another category of SIC. Alternatively, the SIC itself undergoes periodic revisions (e.g., 1980, 1992, 2003 and 2007 in the UK), which can result in a reclassification of activity even if the firm in question does not substantially alter its production activities. Inter-temporal comparisons can thus be complicated, especially at higher levels of disaggregation down to the firm and unit operation level (Figure 2).

In light of these shortcomings, several alternative classifications for industrial activity have been proposed. One is based on the degree of homogeneity of the output from individual subsectors

and is therefore useful for energy efficiency benchmarking purposes (Entec UK Ltd. & NERA Economic Consulting 2005). An alternative, similar classification is based on the processes carried out by firms (Beyene & Moman 2006). This would be especially useful for energy analysis of industrial activity, especially when the large variation in processes across industry are taken into account (see Section 1). A strong argument for establishing this kind of taxonomy is that major policy and funding decisions are dependent upon the relationship between the subsector and its energy intensity.

4. Energy and Exergy Analysis

Method. Energy and exergy analysis have been widely applied to macro- and microeconomic systems to determine operational efficiencies and potential for energy savings. Whereas energy analysis is strictly based on the First Law of Thermodynamics or the idea of an energy balance applied across a system (Slessor 1978, cited in Hammond 2007), exergy analysis incorporates both the First and Second Laws.

Energy is associated with a *quantity* of energy (i.e., enthalpy), whereas *exergy* refers to the quality of an energy carrier or stream. In other words, exergy is a measure of the ability of an energy stream to perform work. Electricity has a high thermodynamic quality (i.e., thermodynamic quality, $\theta=1$), for example, because of its ability to provide motive power and heat, but low-temperature hot water has a relatively low exergy content ($\theta \approx 0$) because its ability to perform work is limited – it is only really useful for space heating.

Exergy analysis explicitly captures the thermodynamic irreversibilities occurring in energy conversion processes and thus identifies the necessary and avoidable losses. The majority of the unavoidable exergy destructions occur in combustion processes, when chemical exergy is converted into useful physical exergy (Hammond 2007). Exergy analysis can be used to identify the potential for heat cascading, because, according to the First Law of Thermodynamics, high-quality energy can be reused lower down the quality scale. It must be used in conjunction with other, complementary techniques, however; alone it cannot provide enough information about an energy system to draw full conclusions.

The exergy function itself is an extensive property (Szargut *et al.* 1988; Hammond & Stapleton 2001), which is

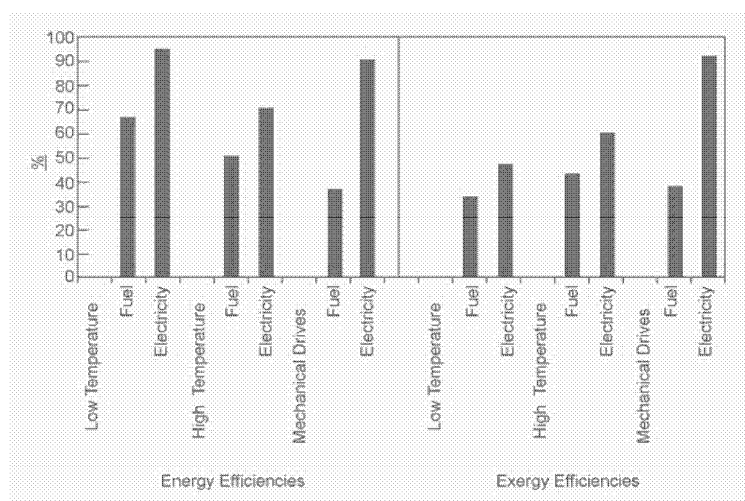


Figure 3. Thermodynamic efficiencies of industrial processes (Hammond & Stapleton, 2001).

defined by reference to a 'dead' or equilibrium state (in terms of temperature T_o , pressure P_o , and species component μ_{i0}):

$$E = (H - H_o) - T_o(S - S_o) + \sum_i N_i(\mu_i - \mu_{i0}) \quad (1)$$

where H denotes the enthalpy of the energy carrier, S the entropy, and N_i is the number of moles of species i . Variations in species concentration are not usually significant in problems related to the macro-scale analysis of energy systems. Consequently, a truncated mathematical expression can be used to calculate 'physical' or 'thermomechanical' exergy states:

$$E = (H - H_o) - T_o(S - S_o) \quad (2)$$

The choice of reference state has been the subject of some divergence of opinion in the literature. A common basis for heat load calculations in the UK is to assume a winter outside design temperature of about -1°C .

Results. To analyse energy usage and its effectiveness within the industrial sector, it is convenient to subdivide the multitude of processes into four broad categories: low temperature ($T_p < 394$ K), medium temperature ($T_p = 394 - 692$ K), high temperature ($T_p > 692$ K), and mechanical drives. Hammond and Stapleton (2001) employed this categorisation to study the exergetic 'improvement potential' in the UK industrial sector. They found that the overall exergy efficiency of this sector ($\sim 46\%$ in the mid-1990s) was much

lower than the corresponding energy efficiency ($\sim 69\%$), although the disparity was not as large as in the domestic sector, where space heating predominates.

Figure 3 shows the large differences between the energy and exergy efficiencies of low- and high-temperature industrial process and of mechanical drives. Whereas the energy efficiencies are relatively high, the exergy efficiencies are typically much lower, which indicates significant thermodynamic improvement potential.

The exergy method has also been employed to analyse the industrial energy demand of several industrialised countries, including the Netherlands and the former West Germany (van Gool *et al.* 1989). To perform such a broad analysis, an energy demand-temperature profile is required for industry in approximately 100°C bands. Hammond (2007, based on van Gool 1987 and van Gool 1992) has produced an indicative demand profile for the industrial sector of the (former) EU-15 countries, which is based on data relating to the Netherlands and former West Germany. Some approximations about the way energy and exergy are consumed in different processes allows the conversion of this profile into an enthalpy/quality diagram. This facilitates the identification of the scope for energy (or heat) cascading as a means of improving the thermodynamic performance of the sector. These diagrams should be treated with caution, however, because they

strictly only indicate the theoretical potential for thermodynamic improvement. As such, they do not consider the temporal and spatial constraints on transporting and utilising heat over large distances.

An energy demand-temperature profile does not currently exist for the UK. Hence, the emphasis of current work is on developing such a profile based on detailed bottom-up modelling of the industrial sector. It is based on a large number of sources, including IPPC (Integrated Pollution Prevention and Control) sector guidance, trade associations' information and data from plant manufacturers. A schematic of the model is shown in Figure 2, in which the two separate aspects (i.e., top-down and bottom-up) of the model are clearly identified. These two aspects interface at the highest disaggregation level of the SIC and therefore serve as validation for one another.

5. Concluding Remarks

The use of thermodynamic analysis has been presented in the interdisciplinary context of industrial energy analysis, including the policy background against which industrial activity occurs and some issues associated with its measurement.

Energy options are inevitably constrained by thermodynamic limits on individual plant types and the sector as a whole, but energy policy advice to governments tends to be dominated by views from the social sciences (Hammond, 2004). Thermodynamic ideas, by contrast, often appear esoteric to the non-specialist. Other methods for generating policy advice, including those from the discipline of economics, will not provide substitute insights to those of energy and exergy analysis. However, thermodynamic techniques such as these should not be used alone, but as part of a broader interdisciplinary 'toolkit' of sustainability assessment methods.

In terms of the outlook for the UK's industrial sector, in the short term the priorities for the industrial sector are relatively clear. Here there are a variety of available technologies that can enable energy demand reduction in industrial processes, boiler operation, compressed air usage, electric motor efficiency, the effectiveness of heating and lighting systems, and other ancillary uses (such as transport). Around 350 separate combinations of subsectors, devices, and technologies have been identified as having potential

for energy savings in industry (Dyer *et al.*, 2006). However, the prospects for the commercial exploitation of innovative technologies by the middle of the 21st century are highly speculative. Emphasis is therefore laid on the range of technology assessment methods that are likely to provide policy makers with a guide to progress in the development of high-temperature processes, improved materials, process intensification, and improved industrial process control and monitoring.

It is in these areas that thermodynamic analysis can make a major contribution to identifying where process improvement potential lies. By employing such approaches as enthalpy/quality diagrams, the theoretical scope for energy (or heat) cascading within the industrial sector can be determined. To carry out this type of analysis, data is needed on industrial energy demand in temperature bands, sometimes termed the temperature spectrum: shares of industrial energy consumption are required in 100°C bands up to about 1,700°C. Unfortunately, accurate of this sort are currently available for the UK. Although exergy analysis can provide an indication of the maximum improvement potential available from different enabling technologies, it is important to recognise that this 'maximum' – perhaps an 80% improvement in end-use efficiency in some cases – can rarely be achieved in practice. Technical and economic constraints will limit the improvement potential to something closer to 30%.

6. Acknowledgments

The wider research by the authors on industrial energy demand and carbon emissions reduction currently forms part of the Demand Reduction Theme of the UK Energy Research Centre (UKERC). UKERC has directly supported the contributions of the first author (CHD) and the third author (RCM). The authors also appreciate the care with which Gill Green (University of Bath) prepared the figures. The authors' names appear alphabetically.

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8. About the Author

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A1.3 Conference paper presented at the Fourth European Congress on the Economics and Management of Energy in Industry (ECEME14), Porto, Portugal, November 2007

4th European Congress on Economics and Management of Energy in Industry
(ECEME1) in Porto, Portugal, 27th-30th November 2007

Energy and Exergy Analyses of the UK Glass Sector

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Keywords: Energy, Exergy, Thermodynamic Modelling, Glass Furnace

Abstract

Glass manufacture is a very energy-intensive activity in which the furnace accounts for around 75% of energy consumption. Theoretical furnace energy requirements differ somewhat from those achieved in practice for various reasons, especially the temperature difference required for heat transfer and losses through the superstructure. A general model of a cross-fired container glass furnace has been developed, in order to determine the causes of these inefficiencies. In the baseline case, with a pull rate and cullet fraction of 500t/day and 50% respectively, the energy and exergy efficiencies are 51% and 25%. With suitable reconfiguration of the input parameters, the results of the model are in good agreement with other published studies. Some refinement is needed in order to more precisely determine the reasons for thermodynamic losses.

1. Introduction

a) Background

Glass manufacture is a very energy-intensive activity which requires significant fossil fuel inputs at a high capital cost. The glass sector also produces significant quantities of combustion and process related carbon dioxide (CO₂) emissions, and is therefore covered by the EU Emissions Trading Scheme (EU ETS). Hence there are strong drivers for reducing the energy costs and emissions associated with melting (Dyer et al., 2007).

In 2005 the UK glass sector accounted for some 22PJ (1.5%) of total industrial delivered energy use (DTI, 2007). This energy was mainly used in the production of container and flat glass, which account for approximately 61% and 27% of total production by mass (British Glass, 2004). Container glass is mainly used in the food and beverage sector, whereas flat glass has applications in the construction and automotive industries. In 2002, domestic output of container and flat glass was 1.70Mt and 0.70Mt respectively (ibid.). These values currently (2007) stand at 2.3Mt and 1.0Mt respectively (A. Hartley, British Glass, private communication, June 2007).

In general the industry is concentrated in the Yorkshire area, largely because of the abundance of sandstone and limestone deposits in the vicinity (BGS, 2006). Coal

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was conventionally used as a fuel and its profusion in the region was also a key factor in situating furnaces. Silica (from sand) and calcium oxide (from limestone) are major raw materials in (the most common) soda-lime glass, and they account for 72% and 11% of the virgin batch. The remainder is 13% sodium oxide (from soda ash) alongside 4% other minor ingredients, which depend on the specific application for the glass. Approximately 1.9Mt of the UK's 3.9Mt of total annual production capacity is situated in this region.

b) The Furnace

The furnace typically accounts for 75% of the energy used in glass manufacture (European Commission, 2001) and all of the process-related, as well as 90% of the combustion-related, CO₂ emissions (Enviros Consulting, 2006). The combined combustion and process emissions of CO₂ for the sector amount to 1.8 MtC (DEFRA, 2007).

The state of the art for both types of glass manufacture is cross-fired or end-fired regenerative furnaces, with roughly 50% of UK capacity met by each type. Hot combustion and batch gases pass through a regenerator, where some of their heat content is recovered when the direction of the flow is reversed (typically every twenty minutes), and the pre-combustion air is preheated. Furnaces operate continuously in campaigns of ten to twelve years for container glass and up to fifteen for flat glass.

Natural gas is the main fuel used in the UK, which is supplemented by fuel oil in some cases, as well as electrical boost. The latter, although economically expensive, can be used to increase furnace capacity and glass consistency by creating convection currents within the molten bath (A. Hartley, *ibid.*).

c) Theoretical and Actual Energy Requirements

Analytical thermodynamic approaches have allowed the theoretical minimum energy requirements for glass melting to be determined, which is known to consist of three main components (Kröger, 1953; Beerkens et al., 2004). Typical values for these three components are depicted in Table 1.

Source	Hartley, 2004	Beerkens et al., 2004	European Commission, 2001, p.73
Temperature of glass (°C)	1300	1400	1500
Theoretical SEC (GJ/t)			
1. Enthalpy of glass	1.58	1.75	1.89
2. Heat of reaction	0.56	0.52	0.49
3. Enthalpy of batch gases	0.61	0.10	0.30
Theoretical total	2.75	2.37	2.68

Table 1 – Theoretical Energy Requirements for Glass Melting (0% cullet)

These values are based on using only raw materials. However, there is an energy saving resulting from using cullet, because of the heat of reaction is not required, and no batch gases are produced. The theoretical energy requirement for a batch consisting of 100% cullet is therefore around 1.2GJ/t less than that for wholly raw materials.

In practice the specific energy consumption of glass furnaces depends on a number of factors, including:

- **Furnace type** – end-fired furnaces are more efficient than cross-fired ones; container furnaces have a higher thermal efficiency than flat ones; typical SECs for container and flat furnaces are 5.4GJ/t and 7.2GJ/t respectively (Hartley, 2007);
- **Furnace size** – an economy of scale is associated with larger furnaces mainly due to the $3/2$ power relationship between contained volume and surface area;
- **Furnace age** – Trier (cited in Beerkens et al., 2004) suggests that the energy consumption of regenerative furnaces may increase by 1.5 to 4% per year, as well as a seasonal variation;
- **Electric boost** – creates convection currents which stir the molten glass and can be used to increase furnace capacity, but is inefficient in thermodynamic terms as well as economically expensive;
- **Oxygen firing** – reduces pollution and direct energy consumption, but proves to be no more efficient in primary energy terms (Ross & Tincher, 2004, p.15);
- **Combustion conditions** – non-stoichiometric fuel to air ratios can result in incomplete combustion, meaning less energy is released by the reaction;
- **Residence time** – along with the required production rate this determines the furnace volume, which largely dictates energy requirements (Beerkens, 2004);
- **Moisture content** – water in the batch adds to the energy requirements of the furnace, as it has to be evaporated off before melting can occur;
- **Cullet fraction** – melting cullet does not require reaction energy nor does it produce batch gases (see above). At constant load, a cullet increase of 10% reduces energy consumption by approximately 2% (Beerkens et al., 2004).

There is clearly a significant difference between the theoretical minimum energy requirements and those achieved in practice. Typical SECs glass furnaces are around double the theoretical minimum, with a large variation across the industry (Ercole, 2004, cf. Table 1). There are several reasons for this, including the temperature difference and residence times which are required for heat transfer to occur from the hot post-combustion gases to the batch ingredients, as well as heat losses through walls and openings. These all require extra energy, which leaves the system in the flue gases and as structural heat losses (Beerkens 2004). The degree to which these losses can be reduced is the subject of the present paper. Attention will firstly be drawn to the theoretical framework of energy and exergy analysis, and applications to glass furnaces, before discussing the model specifications and data sources, highlighting salient results and drawing conclusions.

2. Methodology

a) Background

Several approaches have been made to analysing glass furnaces with thermodynamic techniques. Attempts have been made to understand the relationships between various furnace operational parameters and energy consumption (e.g., Kröger, 1953; Conradt, 2000). Such studies have facilitated a

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better understanding of the fundamental constraints on furnace performance, such as the optimal pull rate for a given furnace, at which the highest possible efficiency is achieved (Conradt, 2000).

Furnaces are required to operate within a range of pull rates due to fluctuations in demand for glass. Higher pull rates than the design condition can theoretically be achieved with a greater heat input, but with a compromise of sub-optimal efficiency. The practical implication is a limit of economically reasonable operation beyond which the marginal increase in quality glass yield for an additional energy input is negligible. Beerkens et al. (2004) have shown that above specific pull rates of approximately $3\text{t/m}^2\text{d}$ there are only very small gains in energy efficiency. With a 50% cullet fraction, based on an international survey of 131 furnaces, the optimum SEC corresponding to this specific pull rate was found to be around 4GJ/t.

Significant resources have been devoted to benchmarking furnaces. Glass furnaces cannot directly be compared from a thermodynamic perspective, however, because of differences in the key operating parameters (see section 1.c)). Adjustments need to be made for, e.g., the cullet fraction and the age of the furnace (see, for example, Beerkens et al., 2004). In the USA several large-scope benchmarking studies have been carried out in recent years, including a detailed industry profile (Office of Industrial Technologies, 2002), and a comprehensive techno-economic assessment of the current state of the art within the field (Gas Technology Institute, 2006). The Carbon Trust (2005) has recently taken the lead in the UK, with a detailed survey of the container glass sector, covering 29 of the sector's 31 operational furnaces in 2003. It found that the container glass industry has halved its SEC over the last twenty years, as well as reducing container weight significantly, which has resulted in an overall reduction in the energy consumption per product of around 60-70%.

Sardeshpande et al. (2007) have developed a novel analytical benchmarking approach, which consists of a parametric model of an end-fired regenerative furnace, validated against actual furnace data from the Indian industry. It is proposed that the model be used for estimating the energy performance of a given furnace design, thereby optimising the design for energy efficiency. The model could clearly also be applied to existing plant in order to identify opportunities for energy saving.

Most if not all of these benchmarking studies highlight the importance of reliable and accurate data, and how the availability of such data ultimately determines the degree of success of the study. In particular, proprietary reasons can inhibit the disclosure of commercially sensitive information to third parties, which is especially the case in the UK, where a small number of firms dominate the industry.

b) Exergy Analysis

Whereas energy analysis is strictly based on the first law of thermodynamics or the idea of an energy balance applied across a system (Slesser, 1978, cited in Hammond, 2007), exergy analysis incorporates both the first *and* second laws. Energy is associated with a *quantity* of energy (i.e. enthalpy), whereas exergy refers to the *quality* of an energy carrier or stream.

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Exergy analysis explicitly captures the thermodynamic irreversibilities occurring in energy conversion processes and thus identifies the necessary and avoidable losses. The majority of the unavoidable exergy degradations occur in combustion processes, when chemical exergy is converted into useful physical exergy, but the detailed mechanisms involved in combustion are not well understood (Hammond, 2007). Exergy analysis can be used to identify the potential for heat cascading, but economic and technical constraints to such potential should always be borne in mind.

The exergy function itself is an extensive property (Szargut et al., 1988; Hammond & Stapleton, 2001) which is defined by reference to a "dead" or equilibrium state (in terms of temperature T_o , pressure P_o , and species component μ_{io}):

$$E = (H - H_o) - T_o(S - S_o) + \sum_i N_i(\mu_i - \mu_{io}) \quad (1)$$

where H denotes the enthalpy of the energy carrier, S the entropy, and N_i is the number of moles of species i . A full exergy balance must consider the components of physical, chemical, potential and kinetic exergy crossing the system boundaries. The latter two components are only significant in the case of relative motion between the system and its environment. For the present case of a glass furnace, the difference in velocity between the inlet and exhaust is assumed to be negligible. For a more thorough discussion of the theoretical background to exergy analysis, the reader is referred to the relevant literature (e.g. Bejan et al., 1996, Kotas, 1985).

c) Applications of Exergy Analysis

The application of exergy analysis to glass furnaces seems to be somewhat esoteric. Wall's comprehensive bibliography of exergy analysis (1992) cites only two studies specific to the glass sector. Additional literature searches have revealed only one other pertinent study (Kozlov et al., 1985). A summary of the relevant studies is presented in Table 2.

Source	Furnace type	Pull rate (t/d)	Melting area (m ²)	Fuel	Energy Efficiency	Exergy Efficiency
de Lucia et al. (1990) ¹	End-fired regenerative	3.5	-	Natural gas	-	10.5
Sun and Xie (1991)	End-fired regenerative	290	22	Heavy fuel oil	35.6	21.5
Kozlov et al. (1985)	Regenerative ²	120.1	148	Furnace oil	19.0	16.2

Table 2: Exergy Studies of Glass Furnaces (¹ 23.5% oxygen enrichment; producing high quality glass; ² Furnace type not reported)

De Lucia et al. (1990) found that the combustion process accounted for approximately 25% of the total exergy loss in the furnace, and was also rather insensitive to the level of oxygen enrichment employed. Chengxu and Jianming's (1991) energy balance suggests a large energy loss to the atmosphere up the flue, but the exergy analysis suggests that this energy is of a low quality and therefore not worthwhile recovering. Kozlov et al. (1985) also point to large differences between the energy and exergy contents of their determined losses, in particular the exhaust stream and the losses through the furnace lining. They also conclude that the

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exergy losses due to combustion and heat exchange, especially in the regenerators and furnace lining, are the most significant in glass furnaces.

d) Furnace Model and Data Sources

A simplified thermodynamic model of a cross-fired regenerative furnace has been set up (Figure 1). The baseline case has a nominal capacity of 300t/d, which is representative of several container glass furnaces within the industry. Energy, exergy and mass balances are applied across the combustion volume, the molten glass bath, the regenerators, and the flue. The fuel used is natural gas, with an assumed composition ratio by mass of 20:80 ethane to methane, and the optional addition of electric boost.

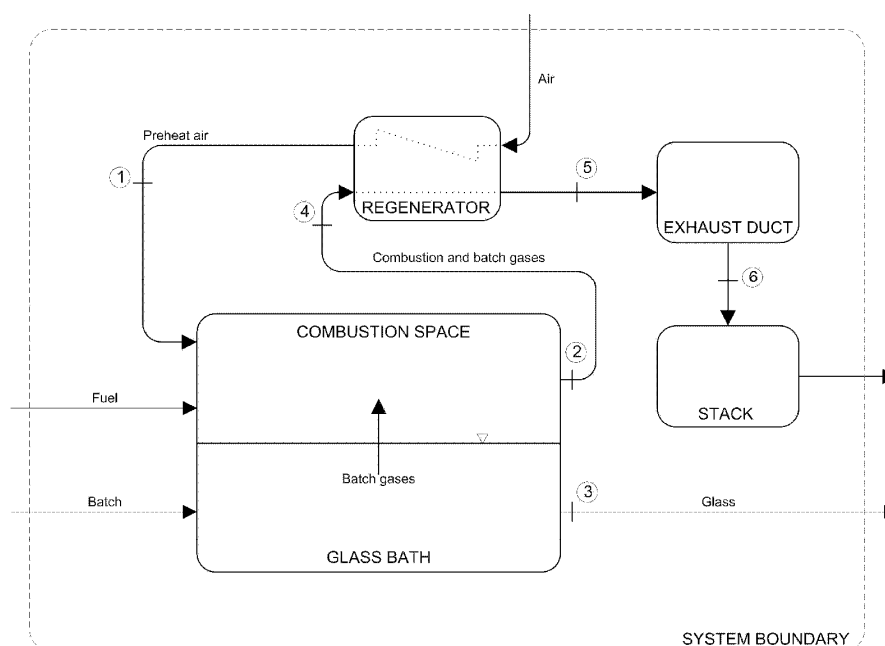


Figure 1: Schematic of Furnace Model showing salient points and flows

Specific heat capacities for standard substances in the environment have been determined from published thermodynamic tables (Rogers & Mayhew, 2000). For the constituents of the batch, the specific heat relationships developed by Sharp and Ginther (1951, refined in Moore & Sharp, 1958) have been used at moderate temperatures, and those determined more recently by Richet et al. (1997) across the glass transition temperature and up to around 1400°C. In the former case, for some of the minor constituents, together accounting for less than 0.1% of the total batch mass, the empirical constants were assumed to be the same as for silicon dioxide, the main batch constituent by mass.

Process temperatures at salient positions within the furnace have been determined from a variety of sources, but most significantly from a patent for NO_x emissions reduction (Quirk et al., 1994). The model's treatment of temperature profiles is two dimensional; it does not consider the heat profile through the length of the furnace,

but instead takes a cross section (Figure 2). Hence the temperatures employed are indicative of averaged values across certain regions rather than precise measurements.

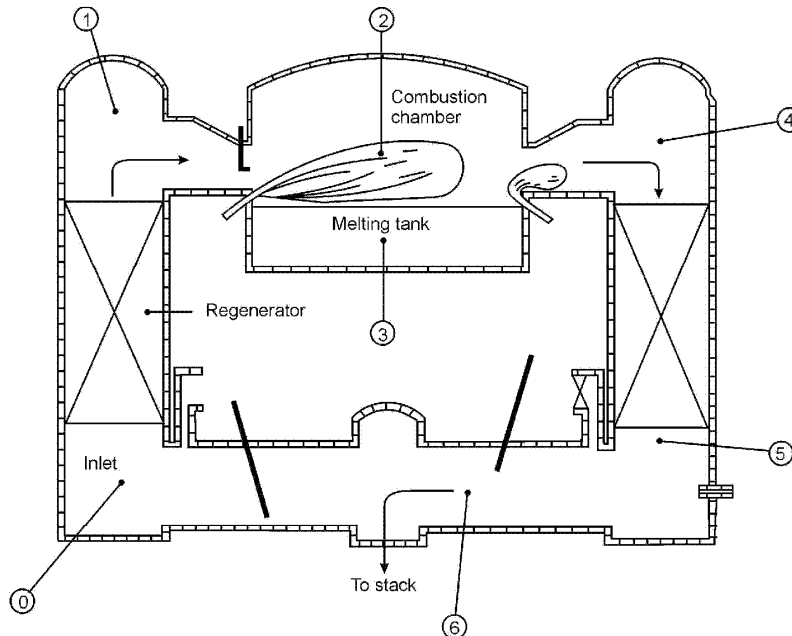


Figure 2: Cross-section through Furnace showing salient points and flows

The chemical exergies of the fuel and raw material have been calculated based on the environmental model of Szargut (1988, cited in Bejan et al., 1996), in which $T_0 = 298.15\text{K}$ and $p_0 = 1\text{ atm}$. This reference temperature might seem rather high for the UK, but the system boundary is drawn close to the furnace.

In order to represent the variation of furnace SEC with furnace load, a linear relationship of the following form has been employed (The Carbon Trust, 2005, p.6):

$$\text{Furnace energy (GJ/d)} = \text{Holding heat (GJ/d)} + \text{Load (t/d)} \times \text{Constant (GJ/t)} \quad (2)$$

whereby the average holding heat was found to be 352.8GJ/d and the load constant was 4.4GJ/t. The resulting furnace energy has been scaled by the cullet fraction, based on the assumption that an additional 1% of cullet addition to the batch results in a reduction in the furnace SEC of 0.29% (Beerens et al., 2004, p.49).

The batch composition (excluding cullet) has been specified in correspondence with British Glass, the trade association for the glass industry in the UK. It is thought to be fairly well representative of a typical batch currently used to manufacture soda-lime container glass. The moisture content in these raw materials is assumed to be 4% by mass in the baseline case.

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The cullet fraction is one of the key variables in the model. Based on this value, the other raw material inputs are adjusted in order to manufacture exactly one tonne of glass. Cullet is assumed to have the same composition as the finished glass, and also has a moisture content in the baseline case of 4%. As well as the energy requirement, the cullet content also affects the total batch weight, because the decarbonisation reactions only occur with primary raw materials. In other words, with the current batch composition and no cullet, 1.2t of raw material is required to produce 1t of glass; but 1t of cullet produces 1t of glass. The variation in batch mass with cullet fraction has been taken to be linear.

3. Results

a) Discussion

Sankey and Grassmann diagrams for the baseline case are shown in Figure 3. They depict the energy (enthalpy) and exergy respectively, of the flow streams through the furnace. The main energy losses are structural, through the walls and openings, and the enthalpy of the exhaust gases at over 500°C. These two losses account for 19% and 26% respectively of the total energy input, of which 47% enters the glass (including heat of reaction). This compares well with similar studies (e.g. Sardeshpande et al., 2007).

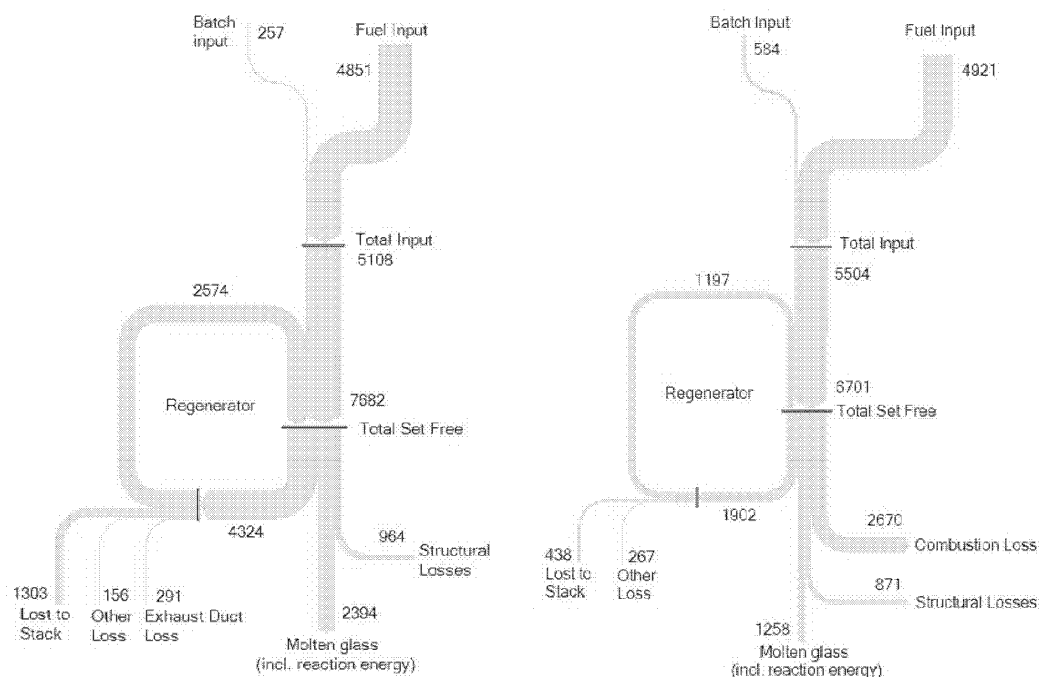


Figure 3: Sankey (left) and Grassmann (right) diagrams for the baseline case (300t/d, 50% cullet)

The main exergy *destruction* within the furnace is due to the irreversible combustion process itself, which accounts for around half (49%) of the total exergy input. The detailed mechanisms involved in combustion are not well understood, but the

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majority of the exergy destruction is thought to be due to internal heat conduction (Hammond, 2007). The largest exergy loss from the system is through the superstructure as radiant heat (16% of total input).

In order to make a fair comparison with other studies, the underlying parameters for the model need to be adjusted accordingly. It is not clear exactly what cullet fractions these previous studies have employed, which impacts heavily on energy requirements. With an output of 120t/d of glass, however, and the same (i.e. 50%) cullet fraction as in the baseline case, the current model has energy and exergy efficiencies of 29% and 14% respectively. The latter corresponds well with the work of Kozlov et al. (1985), although the former is rather high. This is probably due to the present model being heavily based on a larger furnace, which runs at much higher efficiencies. Configuring the model with such extreme input parameters is questionable because they lie outside the region of operation for such a furnace.

Possible modifications to the furnace in order to increase these low energy and, particularly, exergy efficiencies, include improvements to the thermal insulation, in particular to the crown, through which the largest heat loss is known to occur (A. Hartley, *ibid.*). Better furnace and combustion control could also facilitate more optimal combustion conditions, although it is not possible to determine this from the model, which assumes perfect combustion conditions (The Carbon Trust, 2005).

Increasing the cullet fraction is an obvious way to improve the thermodynamic efficiency of the furnace. If 100% cullet is used, the energy and exergy efficiencies of the furnace become 56% and 31% respectively (compared to 47% and 23% in the baseline case). However, there are significant barriers in place to increased recycling (British Glass, 2004; The Carbon Trust, 2005): the Packaging Waste Directive sets mandatory recycling rates and has resulted in growth in demand for alternative uses for cullet (such as in roads); green glass accounts for 18% of furnace output yet comprises 44% of take via bottle banks; and contamination of the waste stream leads to increased energy consumption and, possibly, reject ware.

b) Conclusions

A general model of an industrial glass furnace has been developed, which enables energy and exergy balances to be performed over a range of furnace loads, batch recipes, cullet contents and temperature regimes. The model shows a good correspondence with published data and a sensitivity study has shown that its behaviour is within the expected theoretical limits. Whilst the energy analysis suggests a large energy loss in the waste gases, the exergy analysis indicates a low quality of exhaust, and thus limited utility.

Uncertainties still remain, however, including the effect of velocity on the exergy content of the exhaust gases. Initial precedence studies suggest that these velocities, typically 15m/s, are significantly higher than those of the inlet fuel and air. This indicates that the kinetic energy and exergy components of this stream should be considered in the balance. It would also be useful to refine the model so that the (energy and exergy) losses could be more precisely determined, rather than simply inferred from subtraction, as in the present case.

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A1.4 Article published in Carbon Finance, on the EU ETS's effect on the European cement sector, based on in-depth interviews with senior representatives at several companies (see section 5.4)

CEMENT

Carbon abatement options in the cement sector are becoming harder to find and more expensive, reinforcing the sector's calls for a new approach to target setting, find MICHAEL HERSON and RUSSELL MCKENNA

Time for a new approach?

As a major emitter of carbon dioxide (CO₂), the cement industry – particularly within Europe – has not been slow in addressing the climate change issue. On a sector level, the industry initiated the Cement Sustainability Initiative back in 1999. Many of the leading companies have put voluntary emissions reduction targets in place. On the regulatory front, cement is one of the five sectors that falls under the EU Emissions Trading Scheme (ETS).

To a large extent, the cement sector has weathered the emissions constraints imposed upon it by the EU ETS in its first phase (2005–07). But, as we approach Phase II (2008–12) of the EU ETS, concerns are growing that abatement options may be becoming more limited, and more expensive.

The industry fears that pressures imposed by the current structure of the EU ETS could see production – and therefore emissions – exported beyond the EU's borders. This, they believe, gives grist to their arguments for a new approach to controlling emissions within the sector.

To assess the impact to date of the EU ETS on the European cement industry, The Strategy Works carried out face-to-face interviews with the key personnel at the top five global players: Lafarge, Holcim, Heidelberg, Cemex and Italcementi¹; and a telephone interview with Cembureau, the European trade association for the industry.

Total European sales from these five companies are estimated at €26 billion (\$XX billion) in 2006. Lafarge is the market leader in Europe for cement, while Holcim and Cemex compete closely for second place. Together, these three companies account for some 70% of the turnover among the five companies interviewed.

Demand for cement is growing steadily within Europe at 2–3% per annum. It is proportional to economic development; significantly, Lafarge reports that developing economies now account for as much as 80% of global demand, a trend which is likely to increase in the foreseeable future and which is changing the global landscape of the industry.

Industry efforts to reduce its emissions predate the launch of the EU ETS. Lafarge states it was the first global cement producer to set medium-term targets for CO₂ emissions, in 2001. Other firms followed suit; now all of the five companies interviewed have medium-term targets (for 2010–15) for CO₂ emissions. Public domain information, published within their corporate accounts and annual sustainability reports, confirms that four of the five companies interviewed have reduced their emissions in accordance with their targets to date.

However, the introduction of the EU ETS puts mandatory limits on the sector's emissions. Under the EU ETS, companies are issued CO₂ allowances (EUAs) by national governments based on their reported emissions in previous years, a procedure known as 'grandfathering'. If they emit more than their allocation, they must buy EUAs on the open market. If they expect to emit less, they can sell surplus allowances.

Generally, within the sector, Phase I saw generous allocations in Eastern Europe, but very stringent ones in the West, which Holcim believes is "not a level playing field". By and large, companies were allocated allowances in line with their expected emissions in Phase I.

Firms have been able to transfer their allocations between countries without having to trade on the open market. Three of the five firms appear to be balancing their allocation on an overall, or net basis. Heidelberg "does it on an individual country basis because CO₂ has the same value in all countries". Cemex, meanwhile, will consider trading allowances between facilities or countries in the second phase.

Cembureau reports that Phase I has been "business as usual" for the industry. There is no evidence of a plant closure solely because of the scheme, but some plants have reduced their output or even stopped producing as a consequence of the EU ETS. However, there are concerns that the allocations for Phase II from 2008 will be much tighter. If this occurs, the scheme could effectively act as a cap on production, because it could become uneconomical for the industry in Europe to buy the additional allowances needed to produce (and therefore emit) more than its allocation.

There are several approaches to reducing the emissions associated with cement manufacture, but within Europe at least, two are key. The first involves reducing the amount of clinker in the finished cement, known as 'clinker factor reduction' or material substitution.

Clinker is the main constituent of cement as it provides the strength of the finished product. However, the production of clinker is emissions-intensive, both in terms of the fuel necessary to heat the kilns, and the chemical process that converts calcium carbonate to clinker (releasing large amounts of CO₂).

There are two main alternatives to clinker – blast furnace slag and pulverised fuel ash (PVA, or fly-ash). Slag is a non-metallic by-product of the steelmaking process, while PVA is waste produced when the flue gas from a coal-fired power station is 'scrubbed', which effectively means removing the noxious gases.

The second method of emissions reduction is by using alternative fuels, including organic waste, animal feed and biomass. The emissions saving results from the fact that these fuels are considered "carbon neutral" – on a net basis over their lifecycle, they do not release CO₂.

This results in two savings. First, the CO₂ emitted per unit of energy content is lower than traditional fossil fuels, and secondly, there is an indirect saving associated with recovering these waste products. If they were not used in the cement kiln, they would either be landfilled or incinerated, both of which result in their CO₂ being released to the atmosphere (although the EU ETS does not provide credit for avoiding these emissions).

Material substitution is by far the most efficient means through which to reduce cement emissions. This is because around 60% of emissions are released from the chemical processes occurring inside the kiln, and the remaining 40% come from the burning of the fuel. Material substitution targets both of these sources, because less clinker is required in the first place, which also means

¹ The individuals are: Vincent Mages, vice president, climate change initiatives, Lafarge; Bruno Vanderborght, vice president, environmental strategy, Holcim; Rob van der Meer, director, EU public affairs, Heidelberg Cement; Luis Trevino, director, energy and CO₂, Cemex; Xavier Blutel, group vice president, environmental affairs, Italcementi; and Claude Loréa, technical director, Cembureau

less fuel. Fuel substitution, on the other hand, reduces only the fuel-related emissions.

Companies vary in the degree to which they are pursuing these two routes. The market leader for material substitution is Holcim, with around 27% of alternative materials, including gypsum, being used in its cement in 2006, while the figure for most other companies was approximately 10%. Heidelberg is the market leader in use of alternative fuels with around 16% of its total fuel input in 2006 coming from sources such as biomass, tyres and plastics.

However, there are limits to the above methods of reducing emissions. Generally speaking, material substitution cannot exceed about 75% of total cement composition for slag and 25% for fly ash.

Companies also report quality being a limiting factor for fly-ash: it is often contaminated and requires further processing before it can be used in cement. Lafarge states that this fly-ash quality issue will become more significant in the future because "power generators will have increasing constraints on their emissions in the future," meaning that the fly ash will contain rising levels of contaminants.

Italcementi also reports that many of its clients are willing to pay more for a higher clinker content, which acts as a limit to the material substitution rate.

Slag, on the other hand, appears to be limited in supply. Cemex concedes that there is "no sign of a possible increase of slag production in Europe". Only companies with long-term contracts therefore have a guaranteed supply. Interviewees were reluctant to divulge their sources of supply, but Lafarge claims to have secured long-term contracts with steel manufacturers. Holcim has a vertically integrated approach and "owns and operates slag granulation plants at a couple of steel companies", such as Arcelor in France and Salzgitter in Germany.

Furthermore, even this limited supply is threatened. Heidelberg reports that "new steel plants do not produce granulated blast furnace slag – it's not part of the process". Italcementi foresees a problem within two generations (given the c 50-year lifecycle of a steel plant) in that "the bulk of the steel production is still made from the traditional process, but unfortunately that's true for emerging countries like China and less and less in Europe or in North America, where new technologies recycle scrap iron".

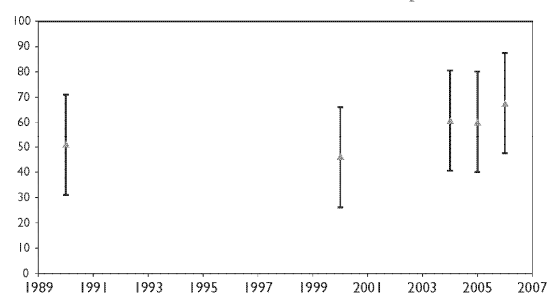
The industry is also facing growing competition for carbon-neutral kiln fuels. In biofuels, there is a distortion of competition from the power sector; not least because this sector receives so-called green certificates for burning these renewable fuels. Italcementi points to "a 'double-penalty' from the power sector". Electricity generators can afford to pay a higher price for biofuels because they pass it on to the consumer. They receive credits for using renewables, which certify that the electricity generated is 'carbon free'. But they can also benefit by selling the resulting excess of EU ETS permits.

The interviewees estimated an average carbon price during the Phase II of €25/t, perhaps even reaching €35/t. €30 per tonne of carbon corresponds to a price increase in the finished cement of about 30%. However much customers value the brand, states Lafarge, "they will not accept such a price increase". The company warns of a future scenario in which the industry is driven out of Europe: "It could generate delocalisation by transferring demand to non-European suppliers. That's the challenge we are facing now."

Cembureau suggests the EU ETS is ineffective in its focuses on carbon reductions in Europe: climate change is "a global problem", to which the EU ETS is an attempt to find "a European solution".

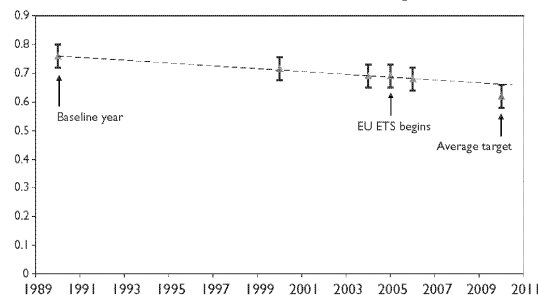
The fear is that, if the carbon price does rise as anticipated during Phase II, the scheme will act as a cap on production within Europe. It might then become economical to import cement or clinker from outside the EU, which would defeat the very object of the EU ETS.

Reported global net emissions (MtCO₂)*



* Mean value over five companies; 2004 and 2000 are averages based on four and three companies respectively
Source: published company sustainability and annual reports

Reported specific net emissions (tCO₂/t cement)*



* Mean value over five companies; 2004 average is based on four companies
Source: published company sustainability and annual reports

Many of the firms state that this is not their intention, but it might be the only option in a worst-case scenario. Cembureau believes this "would be the worst solution". The irony is that overall emissions would actually increase, because of those resulting from ocean transport.

An obvious solution is to change the way the EU ETS operates for the European cement industry, and rethink the grandfathering approach. Lafarge believes that "it's not the right way of calculating future allocations ... it's imperfect".

Cembureau, along with most of the firms, favours a worldwide benchmarking approach instead of the grandfathering. This would establish an emissions intensity benchmark, based on best practice, against which performance would be measured. As benchmarking is performance-related, it rewards efficient operation. This is the opposite of the grandfathering approach which, by allocating permits based of previous activities, effectively rewards the heaviest polluters and punishes the 'good guys'.

Cembureau proposes "to combine the cement industry worldwide, to have defined specific performance to be achieved which is per tonne of product".

Any future scheme clearly needs to be global. The association favours a scheme which "either encompasses the OECD and the major developing countries or protects countries in the lead of CO₂ reduction, from competitive distortions".

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A1.5 A Stern Warning?¹

The Stern Review of the Economics of Climate Change (Stern, 2007, hereafter the Review) has provoked considerable discussion since its completion in October 2006. Its headline figures indicate that business as usual climate change stands to reduce welfare by an amount equivalent to a decrease in per capita global consumption of between 5% and 20% (HM Treasury, 2006, p.x). At the upper limit, this figure is an order of magnitude larger than existing studies on the economics of climate change (The Economist, 2006b).

From the outset the Review is based on putatively sound science regarding climate change. The opening chapter provides a fairly comprehensive overview of the status quo in climate change science. However, it does not seem to fully address the problems associated with climate modelling. Whereas the economic aspects of the Review are abundant with reiterations of risk and uncertainty, there is little or no reference to the uncertainty of these climate models. The only caveat seems to be that the “accuracy of climate predictions is limited by computing power” (Stern, 2007, p.10). The coupled, non-linear and chaotic nature of the global climatic system means that accurate long term forecasts are not possible. From the IPCC modelling scenarios the Review selects the most extreme case – A2 – which predicts around 5°C of warming by 2100 (BBC Radio 4, 2007). The most recent IPCC (2007, p.13) work at the time of writing suggests a mid-estimate of around 2.5°C, however.

In response to the Oxonia Discussion Paper and Seminar – a keynote lecture at the Oxford Institute of Economic Policy given by Sir Nicholas in January 2006 – several authors criticised the apparent misrepresentation of the scientific evidence at that stage. Byatt et al. (2006) suggested that the Oxonia papers gave the false impression of scientific certainty, and focussed on the risks and dangers associated with anthropogenic global warming. Whilst the current author does not wholly agree with their article, they make some very valid points in relation to the Review’s scientific background. They rightly identify the House of Lords Select Committee’s criticism of the Special Report on Emission Scenarios (SRES), which was employed for the IPCC’s Third Assessment Report in 2000. In particular, the House of Lords’ Report (2006) showed apprehension about the objectivity in the IPCC process (suggesting that some scenarios might have political motivation), doubts about the high emission scenarios, and concerns that positive aspects of climate change had been neglected.

Stern (2006) produced a direct response to this criticism, in which he suggests that Byatt et al. (2006) failed to come to grips with the more difficult economic analysis which lies at the heart of the problem. He justifiably highlights the well established history of “sound basic science” which supports the theory of global warming, pointing out that, instead of lying in the measurement of current climatic changes, the major uncertainty is in predicting their likely future extent. The issue is therefore not existential; it lies in quantifying the problem. He further emphasises that policy must err on the side of caution, by taking the worst case

¹ This short essay won the runner-up prize in the Institute of Environmental Management and Assessment’s (IEMA) Student Essay Competition 2007. It was written in March 2007.

scenarios into account, and by adopting a defensive, precautionary stance. His focus on the economics, however, belies the role that science itself plays, both as indicated in the Oxonia papers and in the Review itself. It is thus difficult to reconcile putting economics at the forefront whilst admitting that the science “actually shapes the economics that follows” (Stern, 2006, p.5). As this is indeed the case, then should these two aspects not have an equal – or at least more comparable – weighting? This question is particularly relevant when, in the conclusions to chapter two, the Review states that “in many ways, the science has progressed further than the economics” (Stern, 2007, p.44). It is questionable whether this is the case.

Byatt et al. (2006, p.5) suggest that a central question to the Review should have been “how far, and in what ways, the treatment of climate change issues by the [IPCC] Panel and its member governments could be improved”. One of the key questions in the original Discussion Paper related to the extent to which the combination of economic, social and scientific aspects in Integrated Assessment Models (IAMs) could be improved. These key interdisciplinary areas seem to have been somewhat neglected in the Review, which can only serve to its detriment. Instead of a completely integrated appraisal drawing on all of these elements, the end product seems to be collection of independent, specific studies. The focus should have been on the methodology as much as on the results. Whereas much attention is drawn to the economic theory – in particular of risk and uncertainty – relatively little has been given to the degree to which the economics and the (physical) science can be effectively integrated.

From a purely economic perspective there have been two specific criticisms of the Review, which both relate to the parameters that underpin the discount rate (The Economist, 2006a; Varian, 2006). There are two economic arguments for discounting the future – or, more precisely, the future utility of consumption. The first is based on myopia and reflects the fact that preference is given to utility in the present. Any future gains in utility are therefore discounted to reflect the intervening time period before they are realised. This is known as the pure time preference rate, denoted by δ in the Review. The second reason for discounting is the marginal increase in future utility caused by a present increase in consumption. If present consumption grows, then society is better off (i.e. “richer”) in the future, such that the same increase, in real absolute terms, is worth less. Hence this justification is referred to as the elasticity of the marginal utility of consumption, η in the Review.

In its central case the Review adopts a value of δ which is essentially zero (0.1%). The argument for this is to account for the small likelihood of part or total extinction of humanity due to some catastrophic event in the future. In defence of this assumption, the Review also suggests that adopting a larger value of δ would be akin to intergenerational treachery, because it would mean taking an unethical stance on climate change towards future generations. The Review also points out the long and distinguished history associated with the discussion of discounting, citing some of the forefathers of neoclassical economics, such as Pigou (1932, pp.24-25, cited in Stern, 2007, p.35), who thought discounting implied that “our telescopic faculty is defective”.

Nevertheless, Nordhaus (2006) believes this figure for δ is much too low. He argues that, were more conventional values employed, such as those used by governments and business, then the Review's drastic results would disappear. The crux of his argument is that such a near-zero pure time preference rate magnifies distant impacts. This is indeed the case, which he illustrates with the example of a climate glitch in the year 2200. If this causes damages equal to 0.01% of output then and thereafter, he asks, what would the mitigation cost be today? The astonishing answer is 15% of world consumption. He also takes issue with the measure of consumption used in the Review, which is in terms balanced growth equivalents (BGE), which "is the certainty equivalent of the average annual consumption loss over the indefinite future...akin to an annuity" (Nordhaus, 2006, pp.10-11). Tol (2006, p.2) also notes that this pure time discount rate is much lower than that recommended by HM Treasury (2003).

On the other hand, whilst he agrees with the value of pure time preference employed, Dasgupta (2006) has criticised the Review's assumption about the elasticity of the marginal utility of consumption. He believes that the low value of δ indicates an egalitarian approach across all generations, but that the low value of η (taken as unity in the central case) in fact seems inequalitarian, showing an indifferent attitude towards equity in the future. Instead, he would favour a value for η of between two and four. He also gives an example to illustrate the point of a constant-population, deterministic economy with no technological change, with δ and η set, as in the Review, at 0.1% and 1 respectively. It is then an easy calculation to show that the current generation ought to save 97.5% of aggregate output for the future (Dasgupta, 2006, p.7).

Notwithstanding these fundamental problems, the Review is certainly an impressive, thorough, and current document (Nordhaus, 2006, p.4), which draws on a wide base of detailed analysis. It is an excellent information source, particularly in relation to the mechanisms through which climate change will affect societies and economies (Hallegatte, 2006, p.2). It emphasises the need to establish an international market price for carbon, which is "an urgent challenge for international collective action" (Stern, 2007, p.530), considered by many as *the* central objective for climate change policy in the short and medium term. In this regard the Review seems to have set a precedent amongst climate change policy documents (Nordhaus, 2006, p.5). Furthermore, in producing the largest estimates thus far of the cost of climate change, the Review has created much scope for future work in this area, not least in order to ascertain more reliably and consistently where the actual economic and social cost of climate change lies.

Whilst there is no guarantee that economic analysis can be effectively employed to determine the true costs of climate change, due to the unprecedented, unique and non-marginal nature of the problem, the Review represents one of the most extensive attempts yet to do this. If the future damages from climate change are indeed of the scale it suggests, however, this methodology is unlikely to be applicable (Hallegatte, 2006). The Review's estimated damage costs are extraordinarily large, which seems largely due to the rather extreme calibration of the underlying parameters; other studies have been implemented with different parameters, yet the same methodology, which have produced much more conservative results.

Finally, there is a lack of sensitivity studies, which should have formed an integral part of the Review. In particular, economists would be interested in the sensitivity of the models to changes in the input parameters – especially those related to discounting, but also more generally for the climate and growth models. Where assessments have been made of the bias resulting from neglecting certain aspects in the Review, these assessments indicate that any simplifying assumptions have tended to lessen the associated costs. The results should therefore be treated as conservative estimates.

It has been suggested that the Review is a political document (The Economist, 2006b; Nordhaus, 2006), and that one of its principle objectives is to motivate America into action on climate change policy. Perhaps by grossly exaggerating the costs of climate change, and hence its economic impact on the Western World, the Review stands to compel the United States into ratifying legally binding international climate policies. Although clearly impossible to maintain with certitude, this claim would go some way towards explaining the alarmist approach adopted. Whether or not the Review will succeed as a political document remains to be seen. To qualify as an academic study, though, it would require a proper peer-review process: it appears to have had no such scrutiny. Such a process should highlight exactly how the Review needs to be adjusted and would also improve its credibility.

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5th European Conference on Economics and Management of Energy in Industry (ECEMEI-5),
Vilamoura, Algarve, Portugal, 14-17 April 2009.

Thermodynamic Analysis of the UK Industrial Sector

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1. INTRODUCTION

1.1 Background

In 1997 the UK adopted a discretionary national goal of a 20% reduction in carbon dioxide (CO₂) emissions below 1990 levels by 2010. This was in addition to the Kyoto target of reducing a basket of greenhouse gas (GHG) emissions by 12.5% on 1990 levels by 2008-2012. Recent trends in GHG emissions suggest the Kyoto target will be met, however it is unlikely that the tighter domestic goal shall be reached, this has been recognised by the UK Government. In the medium-term, even greater emission reductions will be required in order to stabilise the global climate system. The Committee on Climate Change (2008) recently suggested that the UK should adopt a target of reducing GHG emissions by 80% by 2050. Meeting these targets will require widespread adoption of energy efficiency measures throughout the economy. As the industrial sector currently accounts for around 30% of demand-side CO₂ emissions, it has a significant role to play.

The present contribution applies thermodynamic (energy and exergy) methods of analysis to the UK industrial sector, in order to estimate the theoretical improvement potential. In practice this potential will be constrained by economic and technical barriers which might reduce the actual potential to some (say) 30% of the theoretical (Fig. 1). A similar approach was recently adopted by Hammond & Stapleton (2001), which involved analysing the energy and exergy flows through the entire economy over a period of some thirty years. This paper will instead focus on the industrial sector alone in light of recent developments, data and insights, with the aim of providing a better understanding of end uses of energy and thermodynamic efficiencies within this sector.

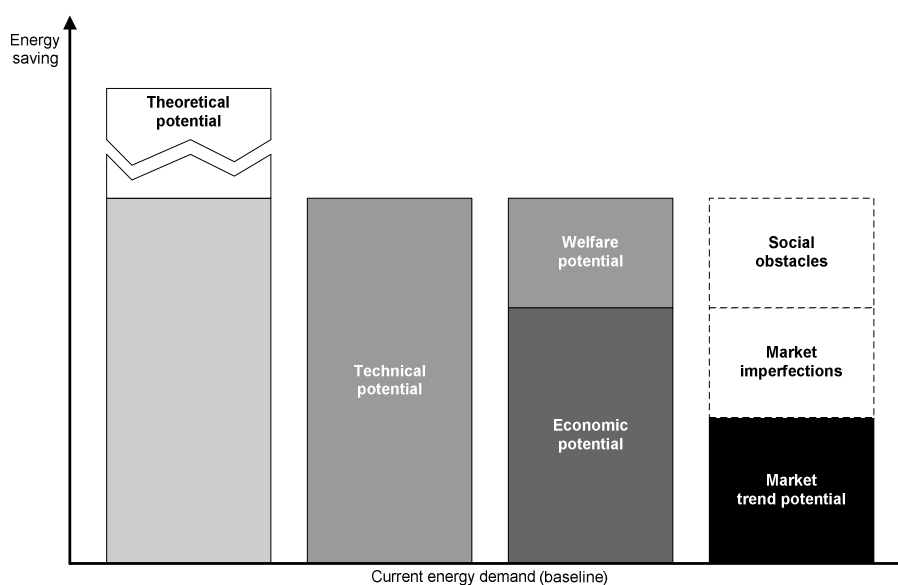


Fig. 1 – Different potentials for energy efficiency improvement (after Jochem, 2000, p.183)

1.2 Character of the Industrial Sector

The industrial sector is the only sector in the UK that has experienced a significant fall of roughly 40% in final energy demand since the first oil price shock of 1973/74 (see Fig 2). This was in spite of an increase in the monetary value of output by over 40% in real terms during this period (Engineering Council, 1998). The consequent aggregate reduction in energy intensity (TJ/£million of gross value added, GVA) masks different underlying causes:

- *Energy efficiency:* The majority of the change in industrial energy intensity is due to improvements in energy efficiency (DTI, 2002, p.32). It has been estimated that around 80% of the fall in industrial energy consumption between 1965 and 1995 was due to this factor (Engineering Council, 1998, p.429).
- *Structural and output effects:* The relative size of the industrial sector has shrunk with a move away from heavy industries. These two effects have been relatively small within the UK over this period (DTI, 2002, pp.33-34, Howarth et al., 1991, Greening et al., 1997).
- *Fuel switching:* Coal and oil use in UK industry has declined steadily since the early 1960s in favour of 'cleaner' fuel such as electricity and gas (Hammond, 1998).

The industrial sector is very diverse in terms of manufacturing processes, ranging from highly energy-intensive steel production to non energy-intensive electronics fabrication (Dyer et al., 2008a). Whereas the former typically employs large quantities of (often high temperature) process energy, the latter's energy use tends to be dominated by space heating. This large variation across industry does not facilitate a cross-cutting 'one size fits all' approach to the adaptation of new technologies in order to reduce energy demand, but rather requires tailored solutions for separate industries. Hence Future Energy Solutions and the Carbon Consortium (2005) identified around 350 separate combinations of sub-sectors, devices, and technologies in their recent study of the potential for carbon reduction from UK industry. Conversely, certain behavioural or good practice measures are suitable for adoption across the board precisely because of their explicit independence from the type of technology employed.

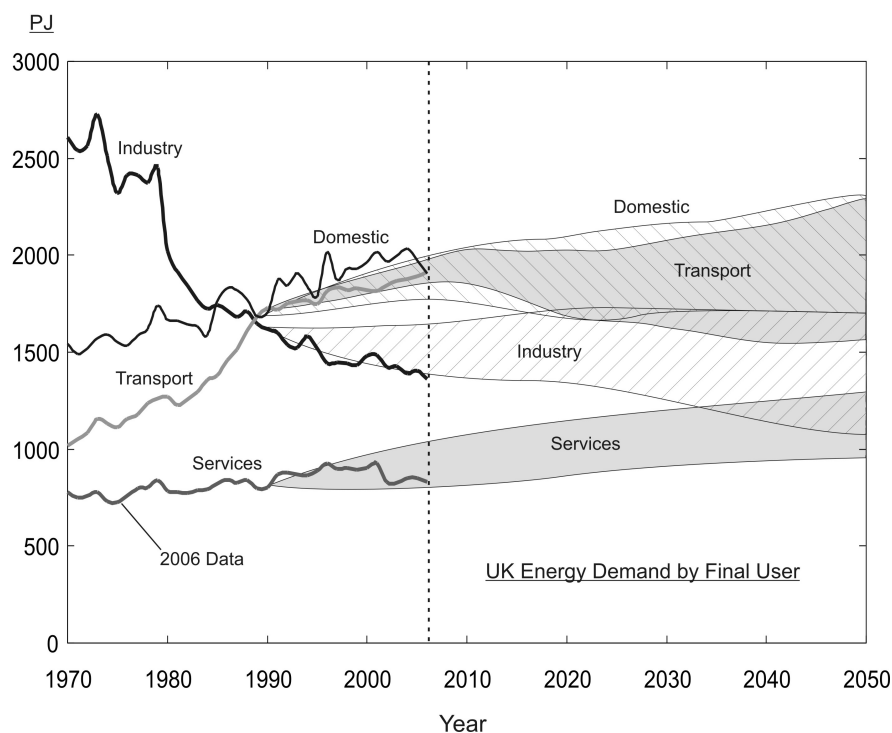


Fig. 2 – UK energy consumption and projections by end use sectors, adapted from DTI (2006) and European Commission (2006).

2. METHODOLOGY: THERMODYNAMIC ANALYSIS

2.1 Energy Analysis

In order to determine the primary energy inputs needed to produce a given amount of product or service, it is necessary to trace the flow of energy through the relevant industrial system. This is based on the First Law of Thermodynamics; the principle of conservation of energy, (Slessor, 1978). It involves the entire life-cycle of the product or activity from 'cradle-to-grave'. This process consequently implies the identification of feedback loops, such as the indirect, or 'embodied', energy requirements for materials and capital outputs. It is therefore sometimes termed Net Energy Analysis.

2.2 Exergy Analysis

First Law or 'energy' analysis, takes no account of the energy source in terms of its thermodynamic quality. It enables energy losses to be estimated, but yields only limited information about the optimal conversion of energy. In contrast, the Second Law of Thermodynamics indicates that, whereas work input into a system can be fully converted to heat and internal energy (via dissipative processes), not all the heat input can be converted into useful work. This suggests the need for the definition of parameters that facilitate the assessment of the maximum amount of work achievable in a given system with different energy sources. Exergy is the available energy for conversion from a donating source (or reservoir) with a reference to a specified datum, usually the ambient environmental conditions. In a sense it represents the thermodynamic quality of an energy carrier, and that of the waste heat or energy lost in the reject stream. Electricity, for instance, may be regarded as an energy carrier having a high quality, or exergy, because it can undertake work. In contrast, low temperature hot water, although also an energy source, can only be used for heating purposes. Thus Hammond (2004) argued that it is important to employ exergy analysis alongside a traditional energy analysis in order to illuminate these issues. It provides a basis for defining an exergy efficiency, and can identify what Van Gool (1992) called the exergetic 'improvement potential' within systems (see Hammond, 2007).

3. ANALYSIS OF THE UK INDUSTRIAL ENERGY SECTOR

In order to analyse energy usage and its effectiveness within the UK industrial sector, Hammond & Stapleton (2001) subdivided the multitude of processes into four broad categories: low temperature ($T_p < 394$ K), medium temperature ($T_p = 394\text{--}692$ K), high temperature ($T_p > 692$ K), and mechanical drives. Typical energy and exergy efficiencies in these categories are illustrated in Fig. 3. The fuel and electricity shares in each of the process categories enabled the thermodynamic inputs and outputs associated with the industrial sector to be estimated. The overall industrial sector exergy efficiency (~ 46% in the mid-1990s) was found to be significantly lower than the corresponding energy efficiency (~ 69%), with the main exergy destructions occurring in irreversible combustion and heat transfer processes. The unavoidable nature of these destructions suggests that attempts at exergetic optimisation should focus on matching the exergy of the supply and demand streams.

Based on more detailed data relating to the end uses of energy in industry (BERR 2008) and improved estimates of the temperature demand profiles of individual industries, it has been possible to carry out a more thorough energy and exergy analysis of this sector. In particular, the taxonomy employed by Hammond and Stapleton (2001) has been refined from three temperature categories to five. In addition, using the above data and drawing on other work in this area by the authors (e.g. Hammond & McKenna, 2007), it has been possible to gain further insights into the split between electricity use for power and heating applications. The latter is obviously thermodynamically inefficient with the current centralised, carbon-intensive and inefficient electricity generation system. But as this system becomes less carbon-intensive and

more efficient (as well as possibly decentralised to an extent) in the future, the same logic does not hold; in this case it might even be favourable to use more electricity over fossil fuels directly. Hence the implications of the current work need to be considered in the broader context of an energy system which is evolving to meet the targets mentioned above.

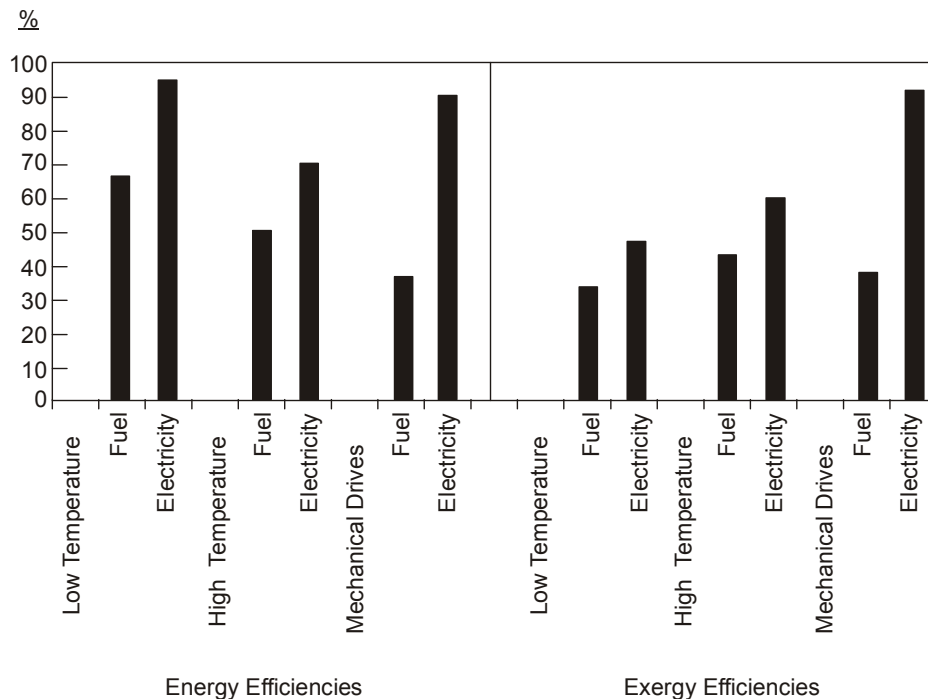


Fig. 3 – Thermodynamic efficiencies of industrial processes (Hammond and Stapleton, 2001).

Industry is arguably the only sector (other than the energy sector) that has such a profound effect on the energy and carbon trends occurring in other parts of the economy, so it is desirable to consider these lifecycle implications of changes to individual processes. Such a strategy requires a major change ('paradigm shift') to an energy system that is focused on maximising the full fuel/energy cycle efficiency, and minimising the embedded energy in materials and products by way of reuse and recycling (Hammond, 2000). Some have attempted to quantify the potential for resource efficiency, including Ernst von Weizsacker et al. (1997) with their 'Factor Four' concept. This suggests that economic welfare in the industrialised world could be doubled while resource use is halved, which would involve a structural shift from energy intensive manufacturing to energy frugal services. In order to make such an approach a practicable engineering option, it would be necessary to use systems analysis methods, including thermodynamics, to optimise the energy cascade.

4. CONCLUDING REMARKS

In the short term, in the period that will rely on the adoption of existing technologies, the road map and priorities in terms of industrial energy efficiency are relatively clear. But the prospects for the commercial exploitation of innovative technologies by the middle of the 21st Century are highly speculative. Dyer et al. (2008a) recently laid emphasis on the range of technology assessment methods that are likely to provide policy makers with a guide to progress in the

industrial sector. Thermodynamic analysis can make a major contribution to identifying where the improvement potential lies. However, it is important to recognise that this ‘maximum’ – perhaps an 80% improvement in end-use efficiency in some cases - cannot be achieved in practice. Technical and economic barriers will limit the improvement potential to something closer to 30%. Even that would make a significant contribution to energy demand and carbon reduction in UK industry.

Exergy analysis can provide an important tool for the understanding of complex energy systems. Hammond & Stapleton (2001) argue that the feasibility of proposed changes is not as important as a proper comprehension of the thermodynamic processes involved. Hammond (2004) consequently advocated the use of exergy analysis as one tool amongst several quantitative approaches that should be employed to study energy systems. The components of this ‘sustainability toolkit’ would also include environmental life-cycle assessment and cost-benefit analysis. All have their particular advantages and disadvantages.

Recent trends in energy prices, specifically those of natural gas, and the implementation of national and European legislation have resulted in stronger drivers for industrial energy-efficiency technology, such that previously marginal opportunities are becoming economically attractive. However, there still exist many barriers to the uptake of this technology, the most significant of which appears to be ‘ignorance, inertia and lack of interest’ (The Carbon Trust, 2005). Various policy instruments will inevitably be required to encourage the introduction of energy efficiency measures in the face of market barriers. The two main candidates for intervention are economic instruments (carbon and/or energy taxes, and traded permits) and utility regulation in the wider interests of environmental protection.

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Acknowledgements

The funded research of the first author (GPH) on industrial energy demand and carbon emissions reduction currently forms part of the research programme of the UK Energy Research Centre (UKERC). He is grateful to Professor Jim Skea (UKERC Research Director) and to Dr Brenda Boardman (of the Environmental Change Institute at the University of Oxford, who was a UKERC Co-Director and co-ordinates their 'Energy Demand Reduction' Theme), for their support in this regard. This national centre is funded by three of the UK Research Councils - the Economic and Social Research Council (ESRC), Engineering and Physical Sciences Research Council (EPSRC), and the Natural Environment Research Council (NERC). Dr Boardman was succeeded in her post by Dr Nick Eyre on 1st October 2007. The second author (RCM) is supported by a UKERC interdisciplinary research studentship (jointly supervised by Professor Hammond and Dr Adrian Winnett at Bath). Finally, the third author (JBN) is supported by a research studentship co-funded by the Great Western Research (GWR) Alliance, EDF Energy and EDF R&D (jointly supervised by Professor Hammond and Professor Catherine Mitchell of the University of Exeter's Cornwall Campus).

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A2 Background to economics and thermodynamics

This appendix provides an overview of the theoretical foundations of economics and thermodynamics, as well as the methodologies employed in this thesis.

A2.1 Economics

This section is concerned with the economic perspective, with a particular focus on the concept of production. A brief overview of the neoclassical economics paradigm is presented, after which the production function is discussed and a summary of investment appraisal techniques is given.

A2.1.1 Overview of the neoclassical economics paradigm

Embedded in the neoclassical economic paradigm are the “categories” of economic actors, behaviour, institutional frameworks and analysis (Kreps, 1990). Actors behave in such a way so as to maximize their utility, a theoretical or notional quantity that relates to the pleasure or satisfaction gained from consumption of particular goods or services. Individuals maximize utility based on a budget constraint, and firms maximise profits subject to the constraints imposed by their technological production possibilities set. The interactions between actors occur within the institutional framework, which relates the behaviour of individuals to one another. The final category is equilibrium, defined as a situation in which each individual is doing as well as is possible for him- or her-self, given the resources available. Any further addition to one individual’s utility would result in a commensurate reduction in another individual’s utility – the concept of Pareto optimality (Gravelle & Rees, 2004).

Actors are assumed to be wholly self-interested and therefore motivated solely by gains to their own welfare and their decisions are based on the information available to them at any time. Market equilibrium is said to exist when the interaction of supply and demand curves dictates market prices. Focus on one single good or service lead Marshall to the concept of partial equilibrium, so called because it neglects the effects of other marketplace goods and services on this one market (Deane, 1978, p.112). Although a limited representation of reality, partial equilibrium is useful precisely because of its simplicity; it allows the analysis of markets in isolation without the need to consider “coupling” effects and spillovers. A further development of the partial equilibrium model into the general equilibrium framework was chiefly made by Walras (Cowell, 2005). The general equilibrium model further considers linkages between markets, and therefore the effects that changes in the equilibrium price have between markets. The general equilibrium model is at the core of the neoclassical paradigm, and provides the basis for much activity in the field of policy evaluation (in the form of the Computable General Equilibrium, or CGE, model).

The capital employed to drive the economic process exists in various forms (Parkin, 2000):

1. **Natural** – the most fundamental form; the stock of environmentally provided assets:
 - a. Resources – including fuels and raw material inputs;
 - b. Services – such as climate regulation or providing a sink for waste heat;
2. **Human** – all health, knowledge, skills, motivation;
3. **Social** – different cooperative systems and organisational infrastructure, such as families, communities, governments etc.;
4. **Manufactured** – human-fabricated infrastructure that is already in existence, such as tools, machines, roads and buildings; and
5. **Financial** – which has no intrinsic value, its value being purely representative of the other four kinds of capital.

Natural capital is the form from which all others are derived, and is the only form that exists in abundance before human intervention. The economic system employs natural capital as its primary input, along with labour and other derived forms of capital, to produce more valuable capital, especially manufactured or financial. In the neoclassical model, the economy is a closed circular entity around which capital continually flows. This is similar to the concept of the ouroboros that continually devours its own tail, symbolising wholeness or infinity (Figure A1).

Instances in which markets do not function effectively are known as market failures. An externality is a particular form of market failure, in which the consequences of an economic action are not accounted for by the market, and are thus experienced by a third party, outside the market or transaction. It is due to a failure to define and enforce property rights in certain areas of economic activity. An example of an externality is unregulated pollution from a factory flue, which pollutes the environment, yet this effect is not accounted for by the market. An externality exists when both of the following conditions are satisfied (Pearce & Dasgupta, 1972, p.118):

1. Economic activity in **affects the production or utility levels of other producers or consumers** (the interdependence condition);
2. The **effect is unpriced and uncompensated** (the non-price condition).

Economic growth within this framework is defined as an increase in the value of goods and services produced by an economy – that is, output as measured by Gross Domestic Product (GDP), or Gross National Product (GNP)². It is widely held by neoclassical economists to be necessary in order to increase living standards and wellbeing for the population as a whole. Economic growth was long thought to be the sole driver for increased wellbeing, such that this could be measured by increases in per capita GDP or GNP. The field of Development Economics concerns itself with the improvement of individual and social welfare, however, and emphasises the need to consider all aspects of human wellbeing in measuring growth. It has

² GDP is one of the standard measures of output for a nation state, defined as the sum of the value of goods and services produced by the economy, and accounts for subsidies and taxes, as well as the effect of net imports or exports. GNP includes foreign direct investment overseas. Whereas GDP is the output of a nation, GNP is the output of the nationals of that nation, regardless of where it is produced.

produced several alternative measures of human welfare, many of which account for additional factors to GDP or GNP. These include the Gini index, a measure of the degree of national income inequality and therefore the position on the Kuznets curve (Ray, 1998) and the UNDP's (2007) Human Development Indicator (HDI). Sen (1998) has also shown that mortality is itself a robust indicator of welfare; in the USA a Genuine Progress Indicator (GPI) has been developed by Cobb et al. (2007); and in Europe an Index of Sustainable Economic Welfare (ISEW) has been determined for several countries (Hammond, 2000, p.307).

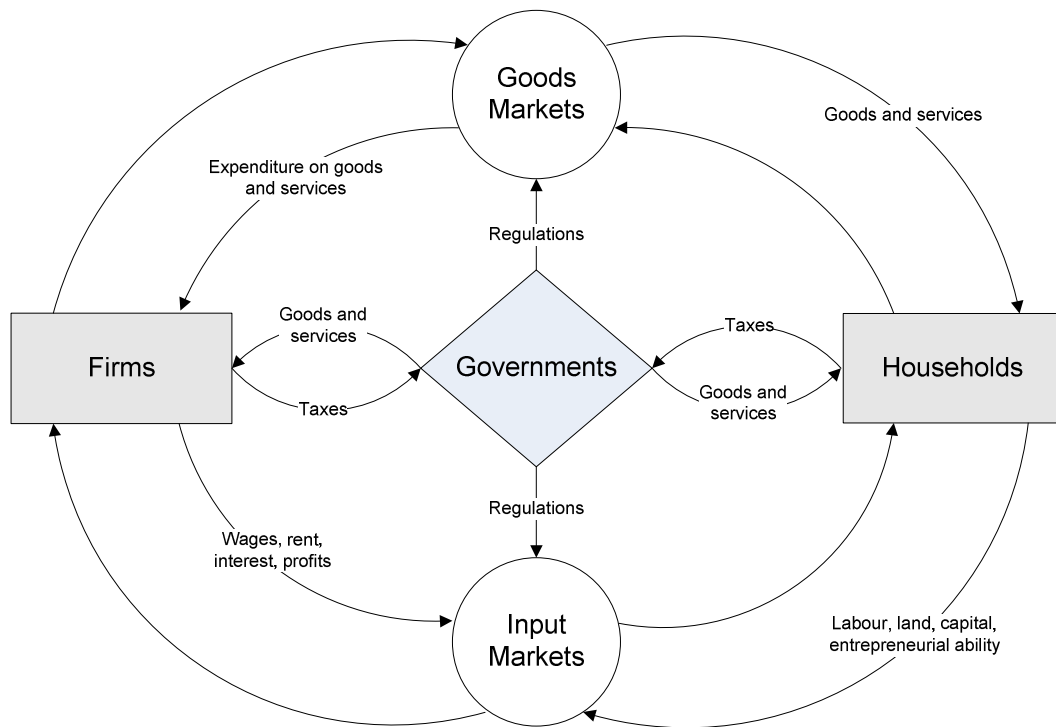


Figure A1 – The neoclassical economic system as ouroboros, incorporating a circular flow of income and expenditure (adapted from Parkin et al., 1997, p.18)

For the UK there has been a widening gap in recent decades between the growth as measured by GDP and that according to the ISEW, which highlights the inadequacy of GDP alone to measure human development. Development economists also stress that an obsession with purely economic growth overlooks issues of, *inter alia*, wealth distribution, public care and social organisation, which all affect the way in which wealth actually impacts individual lives. What is needed is an impartial concern in assessing the real opportunities that individuals have (Anand & Sen, 2000). Furthermore, economic development does not necessarily imply the transition of an economy from a primary, through secondary, to tertiary sector based activities, although this has been the general pattern of development in the West.

A less controversial issue surrounding economic growth is what causes it. For economic growth to occur, sufficient levels of saving and technological progress are required. Differences in saving and/or innovation between economies are generally held to be due to two main factors; firstly, that individuals are motivated to carry out these processes by the prospect of material gain, and secondly, that these individuals must have secure ownership of the results of

their activities (Common & Stagl, 2005, pp.188-189). The emergence of rapid growth in Europe and North America in the past two centuries can therefore be understood as being facilitated by (but not solely due to) the prevalence of private property rights. The consequence of saving and innovation is that either more capital is available for investment elsewhere or it is possible to do more with the existing capital (or both). The former is associated with an absolute (gross) increase in inputs to production and the latter with productivity of the production process itself. One crucial aspect of the neoclassical model for representing and measuring growth is the production function, to which attention is now turned.

A2.1.2 The production function

The production function relates economic outputs to inputs by employing empirical relationships and constants. The production function is generally assumed to be that function corresponding to the highest possible productivity level. Within this framework the firm attempts to minimise costs given a certain level of production and technology mix or, tantamount to the same thing, maximises production at constant costs. The production frontier is thus a theoretical limit of what might be achieved with a given technology mix. Furthermore, the production function assumes that problems associated with achieving the best possible technical efficiency (with a given technology configuration) are solved, and is thus only concerned with allocative efficiency – i.e. the way in which inputs are combined to produce the output.

The production function may invoke decision constraints for the firm, whereby for example only labour input can be varied in the short term because a firm cannot rapidly substitute capital inputs. The same applies for technology configurations, which cannot easily be switched in the short term, but might change in the longer term. Such technological modifications might be catered for by entirely separate production functions for different time periods or by an input factor which caters for technological innovation and/or creativity.

The mathematical form of the function may simply be linear, whereby the inputs are multiplied together and raised to appropriate powers. One such case is the Cobb-Douglas production function, which is especially simple and has therefore been widely used for this relationship. It was originally proposed by Wicksell (Lloyd, 2001) and later tested against empirical evidence by Cobb and Douglas (Douglas, 1976). It has the general form:

$$Q=Q_0L^{\alpha}K^{\beta} \quad \text{A1}$$

where Q is output, L and K labour and capital, respectively, and Q_0 , α and β are empirical constants. Together α and β are known as the output elasticities of labour and capital, respectively. If these exponents sum to unity in Equation A1, the production function has constant returns to scale. If their sum is less than one then returns to scale are decreasing and vice versa.

The empirical evidence for such an equation, which was gathered from a large sample of countries and industries, seemed to suggest that the output elasticities of labour and capital, respectively, were approximately constant in all cases. Another related function is the Leontief production function, a special case of the Cobb-Douglas, which presupposes that inputs to production will be used in fixed proportions irrespective of the level of production. Together these two types of function have been widely employed in theoretical analysis after being previously employed empirically (Chambers, 1989).

A2.1.3 Investment appraisals in industry

This section outlines the general approach for carrying out investment appraisals of projects in industry. Such assessments are widely used in order to support decision of whether or not an investment stands to be profitable. Investment appraisals usually involve discounting the future cash flows from a project into the future because of the time value of money (myopia) and the fact that future generations are likely to be richer than present ones (see Appendix A.1.5). The future cash flows are determined based on estimates of the likely costs and benefits resulting from the project. In the present case, these are the costs and benefits to the firm or individual, although the field of Cost-Benefit Analysis (CBA) attempts to measure wider, social impacts (Boardman et al., 2001).

The net present value is defined as the sum of all the discounted cash flows over the length of the project. Assuming that the investment, I , is not discounted as it occurs in the present, the NPV is defined according to equation A2, where R is the annul revenue, r the discount rate and N the length of the project in years (ibid.).

$$NPV = -I + R \sum_{0}^N (1+r)^{-n} = -I + R \left[\frac{1 - (1+r)^{-N}}{r} \right] \quad A2$$

Other commonly used investment criteria include the discounted payback period, the Internal Rate of Return (IRR), and the discounted benefit-cost ratio. The discounted payback period or break-even point for a project is defined as the year in which the discounted cash flows become positive (i.e. is zero). The IRR reflects the discount rate that would have to be applied in order to make the NPV over the project's life zero. The IRR is subject to some controversy, however, because there are potentially multiple discount rates at which the NPV is zero due to the polynomial nature of the NPV function in equation A2. Secondly, because IRRs are percentages and not absolute values, they cannot reasonably be used to select one project from several projects differing in size (ibid., p.143). This therefore needs to be borne in mind when evaluating the IRR and employing it as a criteria upon which to make investment decisions. Finally, the discounted benefit-cost ratio is simply the ratio of discounted benefits to costs. Clearly any value greater than one is favourable; the higher this value the more attractive a project. (Another related parameter is the simply payback period, which does not require the cashflows to be discounted. It is defined as the total cost, I , divided by the annual revenue, R .)

A useful method of cost estimation for equipment capacities at which costs are unknown, based on capacities at which the costs are known, is known as the “six-tenth” method (Kharbanda & Stallworthy, 1988). The cost of equipment, C_B , at a given capacity, Y_B , can be used to estimate the cost of the same equipment, C_A , at another capacity, Y_A ,

$$\frac{C_A}{C_B} = \left(\frac{Y_A}{Y_B} \right)^n \times t \quad \text{A3}$$

where n is the sizing exponent that can vary between 0.4-1.0 (but wrongly assumed always to be 0.6). The sizing exponent is an empirical constant used to express the influence of increased capacity on cost, e.g. cost is dependent on area while capacity is dependent on volume, and should also take economies of scale into account. The correction factor, t , accounts for the general development in cost since the estimate was made, expressed via the annual projection rate, a , and the exchange rate, r_c , between currencies,

$$t = (1+a)^y \times r_c \quad \text{A4}$$

where y is number of years since the cost was estimated. The total investment cost of a project can be estimated based on the direct purchase cost of equipment with a correlation invoking the empirical “Lang factor” (ibid.),

$$I_{\text{project}} = f_L \times C_{\text{equipment}} \quad \text{A5}$$

where I_{project} is the total investment cost, f_L and $C_{\text{equipment}}$ are the Lang factor and the equipment capital cost respectively. The Lang factor accounts for project costs such as for installation, which are additional to the capital cost. The Lang factor can be applied to existing plants or new equipment, but not to projects where equipment is installed in existing plants. The increase in yearly running cost (operation and maintenance cost) due to investment in new equipment can be expressed as a fraction b of the total project cost for the new equipment, as shown in Equation A6.

$$c_{\text{running}} = C_{\text{project}} \times b \quad \text{A6}$$

A2.2 Thermodynamics

Thermodynamics is the science concerned with energy in general, and more specifically with the relationships between heat, work, and the properties of physical systems. A crucial focus of thermodynamics is on the conversion of energy from one form to another, most often between heat and other forms of energy. Thermodynamics is a branch of the physical sciences, which therefore does not consider the nature of human interactions other than in a physical sense. This section introduces the assumptions, laws and governing equations of thermodynamics and presents the relevant methodologies emanating from this field.

A2.2.1 Fundamentals of Thermodynamics

In thermodynamic terms, a system is a collection of matter within a clearly defined boundary and everything outside the boundary is referred to as the surroundings or the environment. Systems may be closed or open, depending upon whether mass is not or is transferred, respectively, across the boundary (European Commission, 2006d). Systems may be classed as steady-state, in which case the processes occurring within them are constant with respect to time or dynamic. The (internal) energy of a system consists of the sum of the kinetic, potential and internal energies of the system, hence

$$U_T = U_I + \frac{mV^2}{2} + mgh \quad \text{A7}$$

where U_T and U_I are the total internal energy and internal energy respectively, m is the mass of the body in motion, V is its velocity, g is the gravitational acceleration and h is the height with respect to some reference position. In many cases the last two terms may be disregarded because thermal (i.e. internal) energy is much larger in comparison (op. cit.).

Heat can generally be defined as energy in transit between one body and another because of a temperature difference between the two (Eastop & McConkey, 1993). Similarly, work is a form of energy in transition, but is defined as the product of a force and the distance moved in the direction of the force. The sign convention for heat and work generally treats all inputs to the system as positive, and accordingly all outputs as negative.

Enthalpy is a parameter relating to the heat content or potential of a system in relation to some arbitrary reference state. It is defined as

$$H = U + pV \quad \text{A8}$$

where p is the internal pressure and V the volume of the system.

The specific heat capacity of a substance is defined as the amount of energy required to raise a unit mass of that substance by on 1°C *at that temperature* (i.e. it is a function of temperature). There are two notions of specific heat capacity, at constant volume and constant pressure

respectively, depending upon which of these properties is being held (or assumed to be held) constant as the temperature of the system varies. These two specific heats are defined as (ibid.)

$$c_v = \left(\frac{\partial u}{\partial T} \right)_v \quad \text{and} \quad c_p = \left(\frac{\partial h}{\partial T} \right)_p \quad \text{A9}$$

where T is the temperature in degrees Kelvin. Temperature is the measure of the internal energy of a system and is measured on the Kelvin scale, where 0K is defined as absolute zero, the (hypothetical but practically unattainable) temperature at which all matter contains no energy. The volume and temperature dependency of specific heat capacities means that for compressible fluids – i.e. gases³ – this parameter varies with temperature.

Entropy is another crucial concept in thermodynamics, which relates to the degree of disorder of a system in relation to some arbitrary reference state. It is strictly a relative concept, which is measured between two states, and is defined as the integral of the heat exchange between two systems (or processes) over the temperature (Eastop & McConkey, 1993), hence

$$S_2 - S_1 = \int_1^2 \frac{dQ}{T} \quad \text{A10}$$

where S is the entropy and the subscripts 1 and 2 denote different system states.

There are four laws of thermodynamics, which are defined as follows (Rogers & Mayhew, 1992):

- 1 **The Zeroth Law:** two or more systems at the same temperature as a third body are of necessity in equilibrium with one another. This Law is the basis for the measurement of temperature, whereby a body (thermometer) is brought into thermal equilibrium with the system being measured.
- 2 **The First Law:** energy is conserved in all processes. The work obtained from a process can never be more than the heat supplied.
- 3 **The Second Law:** entropy increases through all thermodynamic processes and these processes are irreversible and unidirectional. That is, energy cannot be transferred from a colder thermal system to a warmer one without work input, whereas the reverse process occurs spontaneously. The consequence of this Law is that the efficiency of processes must always be less than unity, with some heat rejected to the environment.
- 4 **The Third Law:** the entropy of a substance in thermodynamic equilibrium approaches zero as the absolute thermodynamic temperature approaches zero. This Law is mainly concerned with low temperature physics and chemical thermodynamics.

³ Strictly speaking liquids, too, are somewhat compressible, but to an extent that can reasonably be considered negligible compared to gases.

The First Law leads to an energy rate balance across closed systems of (Eastop & McConkey, 1993)

$$\dot{U} = \dot{Q} - \dot{W} \quad \text{A11}$$

and for open systems in a steady state condition the energy rate balance is

$$\dot{m} \left(h_1 + \frac{V_1^2}{2} + Z_1 g \right) + \dot{Q} + \dot{W} = \dot{m} \left(h_2 + \frac{V_2^2}{2} + Z_2 g \right) \quad \text{A12}$$

where U is the internal energy of the system, Q is the heat supplied to the system and W is the work input to the system. In the steady-flow energy equation, A12, m is the mass, h the specific enthalpy, V the velocity, g the acceleration due to gravity and Z the vertical height. These energy balances form the bases for energy analysis, to which attention is now turned.

A2.2.2 Energy analysis

Energy analysis (or energy accounting, as it was originally known) developed directly from methodologies pioneered in the 1970s, which embody the “whole system” engineering approach. The methods seem to have been inspired by the first oil price hike in the early seventies, which was a result of the Yom Kippur War in the Middle East and the subsequent oil embargo of 1973 (Hammond, 1998). Thereafter it clearly became desirable to have a more detailed understanding of energy flows.

Energy analysis (hereafter EA) can be broadly classified into two techniques, namely statistical energy analysis and process analysis. The distinction between the two appears to have been clearer in the 1970s than it is now, though. Many studies employ both methods simultaneously, which is largely because the availability of top-down statistical data on energy consumption has increased drastically since the 1970s (for example, see Söllner, 1997, p.185). The distinction is retained in what follows to clarify the methodological difference, although some of the applications might equally be classified belonging to either school.

A2.2.2.1 Statistical energy analysis (SEA)

Statistical energy analysis (SEA) was developed along the same lines and at the same time as Process Analysis by, *inter alia*, Chapman and his team at the Open University in the UK. It is based on widely available sources of relevant data, and involves tracing energy flows through the economy based upon such macroeconomic datasets. This often requires conversion from economic units (£s) into physical units (Js), which can lead to several problems as discussed in section 4.2.

Perhaps the main form of SEA is Energy Input-Output (I-O) Analysis, a technique which can be used to determine the energy flows through macroeconomic systems such as economies and

sectors. The first strictly Energy I-O Analyses were implemented around 1973, simultaneously and independently on both sides of the Atlantic, by Herendeen (1973), Bullard & Herendeen (1975), and Wright (1977). Bullard and Herendeen used 1967 tables disaggregating the USA's economy into 357 distinct subsectors to determine the primary energy inputs into all sectors. Wright also used these tables along with a similar methodology (and 363 economic sectors), but with two key differences. Firstly, he admits imported goods at zero energy cost, and secondly, he assumes that energy is sold at a uniform price to all consumers (Bullard III & Herendeen, 1975). Together these two variations in approach account for the different results obtained by the independent studies (the average difference between the studies due to the fixed price assumption was 12%; due to neglecting imports it was 5%). Slesser (1978, p.132) also notes the problem of a "mixed system boundary" in which imported primary energy is often not accounted for.

Energy I-O Analysis was adapted from the economic technique of I-O Analysis, which ostensibly has its roots in Quesnay's nineteenth century "Tableau Economique" (Peet, 1993). In their present form economic input-output tables were developed by the German/Russian economist Leontief⁴, for which he later received the 1973 Nobel Prize for Economics (Leontief, 1986). The tables are essentially matrices, including elements for the n th sector of the economy, arranged along n th row and column respectively. The main body of the matrix holds data relating to the output, in economic units (typically £s GVA) from one sector that is employed as the input for another. Thus the sum of a given column indicates the total inputs to the sector indicated at the head of the column. Likewise the sum of a given row indicates the total outputs from the sector at the left (conventionally) of the row. The movement of goods and services within a national economy can thus be determined from these tables with relative ease.

The adaptation of this methodology into energy terms is achieved in three steps:

- i. Determination of the value (in £s) of primary energy used to make one unit (£) of product;
- ii. If the prices for the different forms of primary energy are known (in £/J), the amount of energy used to make this unit of product can be determined; and
- iii. When the price of the product is known (i.e. £/t), its energy intensity in units of J/t can be calculated.

It is often the case that products are not suitable for measurement in physical units (e.g. because of their inherent non-homogeneity), in which case the final stage of this conversion is not possible. This is typical for products whose output can only effectively be measured in dimensionless units, such as highly integrated electronics and vehicles. This leaves the energy intensity of the product, in units of energy per value of gross value added (GVA), or J/£, as was the case in a study implemented in the UK by Wright (1977), based on the same tables as

⁴ Ambiguity surrounds Leontief's birthplace; his birth certificates states Munich (IIOA, 2004) but the Nobel Foundation states St. Petersburg (The Nobel Foundation, 2009).

Bullard and Herendeen. It identified only 29 sectors, from a total of 363, which produce sufficiently homogeneous products for conversion to output in units of energy per unit weight (step three above) (Boustead & Hancock, 1979).

Any application of the I-O method has an implicitly large data requirement, with its availability depending very much the country being studied. Even when the data is collected, the large administrative task means that the tables are typically only available several years retrospectively, at which point the data is outdated. Consequently, I-O Analyses mainly focus on “snapshots” of economic activity, invariably at periods several years in the past. The economic matrix is also not readily adapted to include new and nascent technologies. This was originally the case for Uranium for nuclear power generation the 1967 tables of Bullard and Herendeen (1975) for the USA and the later ones of Wright (1974, 1977) for the UK. The delay in publication is not seen by many as a significant methodological problem, though, especially because major structural changes in industry typically take much longer (Roberts, 1978; Peet, 1993).

The method of Energy I-O Analysis is thus useful for a broad coverage at high levels of disaggregation. For smaller energy systems than national economies or sectors, alternative, more detailed data sources are often favourable. Notwithstanding its limitations, it can provide a powerful insight into the macroscopic energy flows through an economic system. It is a general method for which data is readily available, and for which the methodology is widely applicable to study different flows (other than value). Energy input-output tables are easily adapted to indicate the emissions associated with energy use, provided the carbon content of the fuel and its calorific are available (Peet, 1993).

SEA in general is restricted by the data available, its level of disaggregation, and the delay in publication of the databases. The latter does not present a large problem, especially because technology and production systems do not adapt very quickly (Roberts, 1978; Peet, 1993). Furthermore, inaccuracies can result from the aggregation of data up to the sector level and referring all data to the same time period (IFIAS, 1974, pp.70-71). Hence SEA is most suited to broad sectoral or national analyses, which attempt to uncover general trends rather than being highly detailed studies. By definition such studies tend to be retrospective.

A2.2.2.2 Process Analysis (PA)

Process Analysis (PA) differs from SEA in the method of system determination. For SEA the system is ultimately determined by the data available, whereas PA typically involves defining the system and then obtaining the required data. The two methods of SEA and PA can be referred to as top-down and bottom-up respectively.

PA examines an individual industrial system of production, or individual unit operations. Although there were undoubtedly earlier applications of similar techniques, Chapman and the Energy Research Group of the Open University (UK) certainly played an important role in the

development of PA. They published analyses of the embodied energy in materials and fuels (Chapman et al., 1974, cited in Boustead & Hancock, 1979; Chapman, 1977), shortly followed by an energy input-output analysis of nuclear power stations in the UK (Chapman & Mortimer, 1974; Chapman, 1975). This is not to be confused with Input-Output Analysis discussed above, rather it was an early application of PA in which the energy flows into and out of nuclear power plants were analysed. The study was novel in the sense that it demonstrated the gross energy requirement (GER), on a life-cycle basis, for a nominal number of new nuclear power stations. In so doing it clearly showed the dependence of the energy payback period – before a system becomes a net generator of energy – on the scale of the programme. The rate of growth of the building programme thus sets a lower bound on the energy ratio required to produce an energy profit in a specified time (Chapman & Mortimer, 1974).

PA is based on the First Law of thermodynamics, the conservation of energy, or the notion of an energy balance applied to a system. It involves breaking down complex production operations into sub-processes (unit operations) which are not readily disaggregated further. The starting point is the definition of the system boundaries, which must be done with care because these determine what the scope and output of the analysis, and therefore the degree to which it can be compared to other studies. Thus the system is defined based on the question being asked, and the approach is very much application specific. Process Analysis is therefore much more flexible than SEA.

There are several complications associated with the method. One of these is the problem of determining the amount of embodied energy and materials, which enter the system indirectly. Resources are inevitably used to produce the direct inputs to the system, but accounting for them is difficult. This presents the further problem of deciding what degree of regression to apply, which is invariably affected by the availability of data (Figure A2). This can lead to problems of “breaking into the closed loop”, whereby, for example, the energy content of machines used to make a given product depends on the energy content of the material itself (because this is used to make the machines).

In terms of the level of regression required, Boustead and Hancock (1979, p.77) advocate a third order analysis for fuel processing systems and a second order analysis for material processing. This is because operations at third order required to produce the fuel input at second order can account for up to 4% of the system’s energy consumption, and therefore must be accounted for. In general, the energy associated with fuel production must be treated at least one level higher than the primary fuel production system.

The clear advantage of Process Analysis is that it enables the whole system approach to be applied to the desired levels of disaggregation and regression, whereby the former refers to the “horizontal” scope of the system boundary, and the latter indicates the degree to which the “vertical” energy flows are traced back to their source (cf. Figure A2). The only real limitation is the availability of data. It has given practitioners a better understanding of the energy flows

within energy systems of various sizes, and is useful for pinpointing the energy use in systems where the system boundary is case-specific so data does not already exist relating to the system.

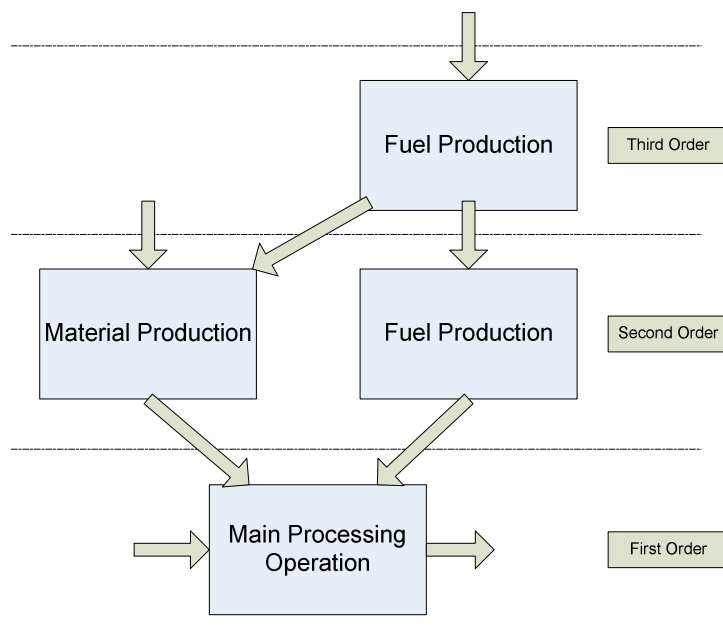


Figure A2 – Orders of regression for processing operations (adapted from Boustead & Hancock, 1979)

A2.2.2.3 Process integration and pinch analysis

Process integration is the common term used for the application of methodologies developed for system-oriented and integrated approaches to industrial process plant design for both new and retrofit applications (Nordman, 2005). Process integration was pioneered in the 1970s against the background of the energy crisis by Linnhoff and his colleagues at the University of Manchester's Institute for Science and Technology (UMIST). One of the most eminent of these techniques is that of pinch analysis (Linnhoff, 1993), which was originally intended as a tool to assist the engineer in designing heat exchanger networks (HENs), but has since become a widely employed tool with which to optimise process plant. It covers a broad array of techniques all aimed at determining optimal design, by considering aspects such as capital investment, energy efficiency, emissions, operability, flexibility, safety and yields.

Three key concepts of pinch analysis technology are composite curves, the pinch principle and the grand composite curve (Eastwood & Linnhoff, 1986). Hot and cold streams are defined as ones that need to lose and gain heat respectively. For any particular process, temperature-enthalpy plots can be drawn that represent the hot and cold streams, referred to as hot and cold composite curves. The relative nature of the enthalpy values means that the curves can be moved horizontally, but not vertically because the process temperatures are fixed. The curves are therefore positioned until the vertical distance between the closest points is equal to the smallest temperature difference between hot and cold streams. The overlap between the two curves on the enthalpy axis then represents the maximum amount of heat recovery possible for the process, and extent to which the curves overshoot compared to one another shows the

amount of external heating and cooling required respectively (Figure A3). The so-called pinch is this point on the temperature enthalpy plot where the temperature difference between the two curves is at a minimum. Once the pinch has been identified, three golden rules must be satisfied for minimum energy requirements (Linnhoff March, 1998):

- i. No heat transfer across the pinch;
- ii. No hot utility (heating) below the pinch; and
- iii. No cold utility (cooling) above the pinch.

If cooling is supplied above the pinch point it needs to be heated again, and if heat is supplied below the pinch point it needs to be cooled again. Heat transfer across the pinch point will increase all heat flows due to this heat transfer. Pinch analysis ensures that the pinch rules are not violated by dividing the process in two separate systems above and below the pinch point. Each system should hereafter be separately designed (Rokni, 2006).

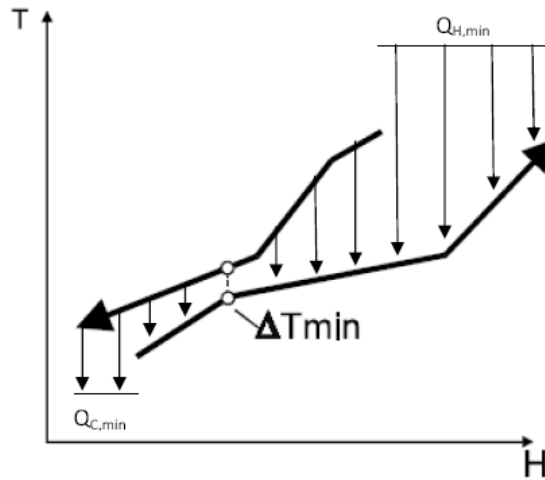


Figure A3 – Vertical heat transfer between hot and cold composite curves

Pinch analysis begins by dividing process streams into temperature intervals, i.e. the first interval is between the highest and second highest process stream temperature. The subsequent intervals depend on the specification of target and availability temperature of the remaining streams. A heat balance can be written for a given interval,

$$\Delta\dot{Q} = \dot{Q}_{\text{cool}} - \dot{Q}_{\text{heat}} \quad \text{A13}$$

where \dot{Q}_{cool} and \dot{Q}_{heat} are the sum of cooling and heating demand of streams in the interval, respectively. The Problem Table Algorithm (Rokni, 2006) can be used to optimize the system with respect to maximum energy recovery, when the temperature intervals are treated as serial connected thermal blocks as shown in Figure A4.

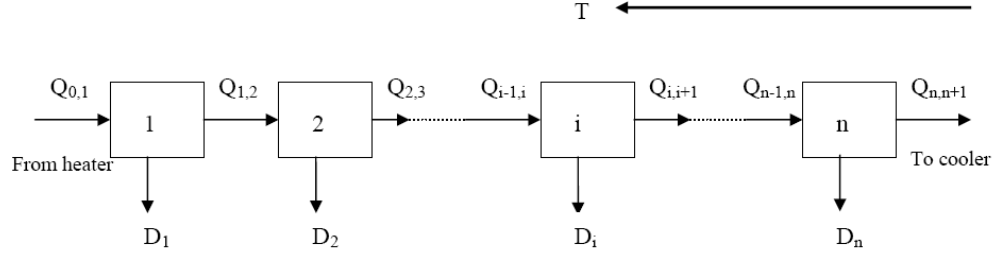


Figure A4 – Serial connected thermal block

The excess energy in each block, D_i , is calculated by means of the heat capacity flow rate ($\dot{m} \cdot c_p$) and upper temperature (T_i) and lower temperature (T_{i+1}) of the block,

$$D_i = (T_i - T_{i+1}) \cdot \left[\sum (\dot{m} \cdot c_p)_{\text{cold}} - \sum (\dot{m} \cdot c_p)_{\text{hot}} \right] \quad \text{A14}$$

If $D_i < 0$, cooling is required for the block, whereas $D_i > 0$ means that heating is required. The energy balance for a given block is

$$\dot{Q}_{i+1,i} = \dot{Q}_{i,i-1} - D_i \quad \text{A15}$$

where $\dot{Q}_{i-1,i}$ and $\dot{Q}_{i,i+1}$ are the supplied and removed heat from the block respectively. The supplied heat to the first block is $\dot{Q}_{0,1} = 0$. The Sequential Balance presents $\dot{Q}_{i-1,i}$ and $\dot{Q}_{i,i+1}$; negative values indicate that heat is transferred from lower to higher temperature, which contradicts the Second Law of Thermodynamics. The highest negative number in the Sequential Balance is therefore added to the all sequential balances and the updated table is known as the Max Table. In the Max Table the minimum external heat supply is given to the first block, because this block now shows the heat added to the system to fulfil the overall heat balance. In the last block the minimum external cooling demand is given, because this now indicates the cooling from the system needed to fulfil the overall heat balance. The pinch point is located where the heat flow between the blocks is zero.

The Grand Composite Curve (GCC) is a graphical representation of the Max Table, where temperature is plotted against the heat surplus in the process (Figure A5). By raising and lowering the cold and hot composite curves respectively, by an absolute distance equal to half of the temperature difference at the pinch, they become superposed at the pinch point. The curves are then plotted in terms of *interval* temperatures, rather than actual ones. If the difference in enthalpy between the two curves is then plotted against this interval temperature, the GCC is obtained (Eastwood & Linnhoff, 1986, p.60). The GCC makes it easier to select the utilities that will meet the energy demand in the most economical way, because it shows where the heat demand and supply is located, e.g. how excess of heat can supply shortage of heat at a lower temperature.

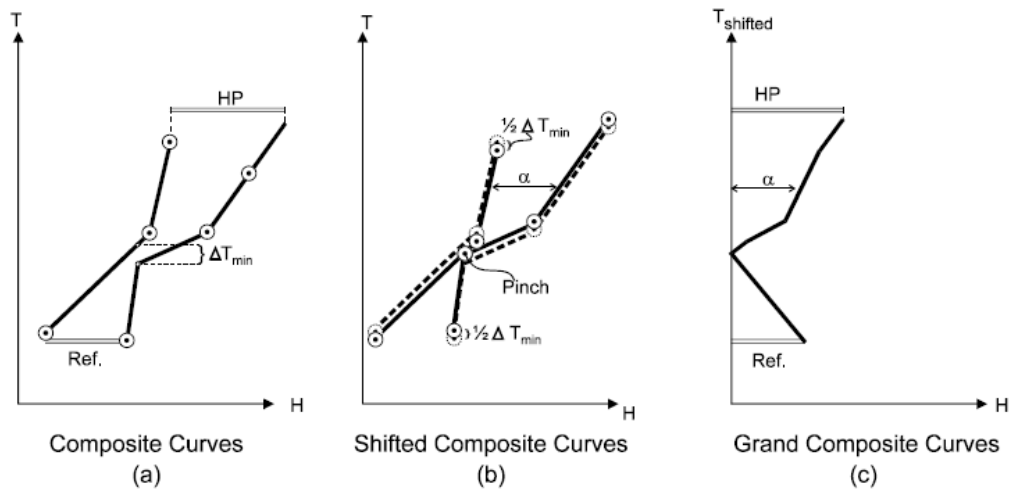


Figure A5 – Construction of the Grand Composite Curve from hot and cold composites (Linnhoff March, 1998)

A2.2.2.4 Emergy

Another related type of energy analysis is that of emergy (embodied energy), which was developed chiefly by Odum (1996, 2003) in the 1970s in response to the need to reflect quality considerations in energy analysis. Emergy is based on the principles of energetics, system theory and systems ecology (Brown & Herendeen, 1996, p.220), and was developed from the maximum power principle, which can be traced back to Lotka (1922). The fundamental principle of this methodology is that the energy used to make a product or service is traced back to the solar energy inputs, both directly and indirectly. Hence to derive the emergy of a resource or commodity, it is necessary to trace all the energy and resource flows and convert them into units of solar energy equivalent. Scienceman (1987) actually coined the term emergy and Odum (1986, 1988, cited in Odum, 1996, p.7) formally defined it as:

“...the available energy of one kind of [sic] previously used up directly and indirectly to make a service or product.”

Embodied energy had already been considered in the field of energy analysis, however, before the emergy concept was coined. The energy embodied in products or services had been used to yield the GER, which Odum regarded as only partially complete because his background in ecology urged him to trace the energy back to the sun (Hammond, 2007b). So the difference is one of boundary conditions, whereby energy analysis draws the boundary closer than emergy, which actually encompasses the sun within its system of analysis.

Brown and Herendeen (1996) highlighted the differences between the two methods of energy analysis and emergy analysis, arguing that the most significant difference is between the form of the energy convention used in the two methods. Whereas emergy considers all different kinds of energy, in solar energy equivalent, embodied energy analysis typically uses the heat energy of the fuel. This distinction corresponds to one between the scope of the system boundaries for the two methods. It also stresses the way in which emergy considers the

qualitative difference between energy carriers. In fact *emergy* appears to have been the first concept to differentiate between the qualities of energy carriers (Hammond, 2007b, p.1115), and might in that sense be seen as a precursor to *exergy* analysis. In this sense it emphasises the heterogeneous nature of fuels and moves away from a focus purely on the First Law.

Emergy analysis has received much criticism, however, and its application has therefore been limited. For example, a keyword search on the ScienceDirect database of peer reviewed journals for the terms “*emergy*” and “*applications*” retrieves fewer than twenty publications, and “*emergy*” returns about 150 compared with around 1500 for “*exergy*”. The main criticisms of *emergy* analysis have been directed towards the link between *emergy* and economics, and the maximum power principle. Odum’s consideration of the transformity of a product as an indication of its economic usefulness is especially controversial, as it implies an *emergy* theory of value (Hau & Bakshi, 2004, p.219). The counterargument that the *emergy* school might offer to this, and which might also be given for any other physical theory of value, is that such an *emergy* value theory can still provide useful insights for sustainable development and is not intended to replace the neoclassical value framework (see section 2.1.4).

The maximum power principle has been criticised because its invocation to explain all systems based its application to self-organising systems is unfounded, and has been likened to an unjustified Grand Unified Theory by Hau and Bakshi (2004). Further confusion has stemmed from the ambiguous relationship that *emergy* has with other thermodynamic concepts such as energy and *exergy*. It claims to be the only one that can qualitatively differentiate between energy carriers, although *exergy* analysis also does this. The confusion seems to stem from a subtly different usage of the term “*quality*”, because in the *emergy* context it is used to refer to the embodied energy contained in different fuels, whereas in *exergy* terms it is the parameter directly related to the capacity for performing work of the energy stream. The lack of formal links between *emergy* and other thermodynamics fields has thus partly contributed to its limited application.

A2.2.3 Exergy analysis

Exergy analysis is the most well-known technique of the group of methods broadly referred to as Second Law Analysis (Kotas et al., 1995). It explicitly considers the irreversibility of thermodynamic processes, because any conversion process has unavoidable losses associated with it. Hence *exergy* analysis relates to the quality of an energy flow, in contrast to the energy analysis, which examines merely the quantity of energy. A thorough review of all Second Law Analysis techniques has been given by Haywood (1974a, 1974b).

The need to determine the work potential of an energy source can be traced back to some of the pioneers in the field of thermodynamics (Carnot, 1824; Gibbs, 1943, both cited in Wall, 1987). The term *exergy* was first coined by Rant in 1956 and has been widely adopted as the convention over the past few decades (Hammond & Stapleton, 2001). Formerly, there were many names for this property, including availability, available energy, available work, work

potential and essergy (Kotas, 1985). Haywood (1974b, Appendix 4) also presents an historical review of exergy analysis.

Exergy can be formally defined as the capacity of an energy resource to perform work, when considered in relation to some reference state, which is usually taken as the ambient environmental conditions (often referred to as the “dead state”). It is considered as the extent to which a system deviates from equilibrium with its environment (Wall, 1987). Baehr’s (1965, cited in Wall, 1987, p.56) universally applicable definition is worth quoting:

“[Exergy is] the totally convertible part of the energy, i.e. that part which may be converted into any other energy form”.

Exergy thus accounts for the “usefulness” of an energy resource, and has been referred to as “what the layman calls energy” (Gaggioli, 1983, cited in Tsatsaronis, 1990, p.7; Ayres, 1998, p.192). For example, electricity has a high exergy content because of its capacity to perform motive work – through a motor, for example – as well as heat – through an electric filament. On the other hand, medium temperature hot water has a low exergy content because of its limited application – for space heating. The exergy method is therefore a useful tool for identifying the point in the energy system where thermodynamic quality is irreversibly lost. This thermodynamic quality parameter increases asymptotically to a maximum value of one as the ratio of the process temperature to that of the environment increases to infinity (Figure A6).

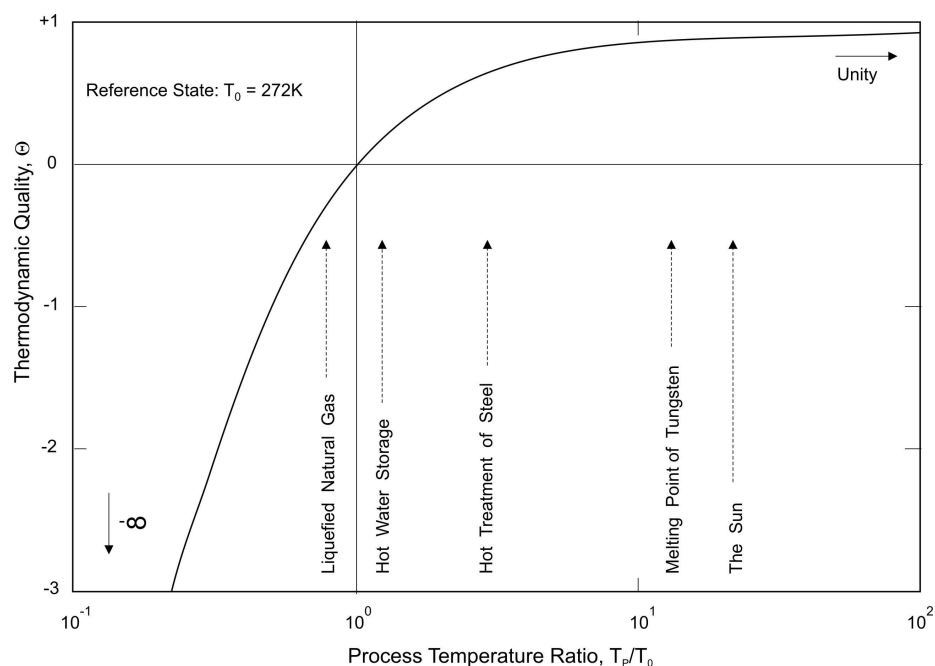


Figure A6 – Temperature Dependence of Thermodynamic Quality (reproduced from Hammond, 2004, p.625)

The exergy of a system is obtainable as the system is brought into equilibrium with its surroundings (European Commission 2006d). It is generally not conserved but is destroyed by irreversibilities. The steady-state exergy balance is given in Equation A16, where the subscripts

i and o refer inputs and outputs respectively, and d and l refer to destructions and losses (Bejan et al., 1996, p.144). The crucial distinction between exergy destructions and losses relates to the former occurring within the system boundary, whereas the latter actually cross the boundary.

$$E_i = E_o + E_D + E_L \quad \text{A16}$$

The total exergy of a system relative to the dead state is defined as

$$E = (U - U_0) + p_0(V - V_0) - T_0(S - S_0) + \frac{mV^2}{2} + mgh \quad \text{A17}$$

where the symbols have their usual meanings. The last two terms may be dropped in Equation A17 because they are usually negligible in relation to the others. The exergy flow across a control volume may be referred to as the physical or thermo-mechanical exergy (Bejan et al., 1996), corresponding to the first three terms on the right hand side of Equation A17. By substituting Equation A8 for enthalpy into Equation A17, and neglecting the kinetic and potential energies, the physical exergy relation shown in Equation A18 is obtained.

$$E = (H - H_0) - T_0(S - S_0) \quad \text{A18}$$

The exergy efficiency is defined as (Hammond & Stapleton, 2001)

$$\Psi = \frac{E_{x_{out}}}{E_{x_{in}}} \quad \text{A19}$$

where $E_{x_{in}}$ and $E_{x_{out}}$ are the total exergy input and useful exergy output of the system, respectively. Finally, the thermodynamic quality or Carnot factor, Θ , relating to the exergy (rate) to energy (rate, i.e. power) is defined, for heat transfer at constant temperature, as

$$\Theta = 1 - \frac{T_a}{T_p} \quad \text{A20}$$

where T_a and T_p are the reference and process temperatures respectively. The quality factor corresponds to the exergy content of the energy, such that electricity has a value of one and heat at room temperature is approximately 0.2 (depending on the reference state).

Exergy analysis was first widely applied in the 1970s, when the Dutch physical chemist Willem van Gool played a significant role in the dissemination of the methodology (Hammond, 2007a). Studies were initially focussed on individual energy conversion systems and process plant. Van Gool (1997) gives an example of using a gas boiler for space heating, which normally has a relatively high energy efficiency but which has a very low Second Law, or exergy, efficiency. This is because much of the energy in the fuel is used to heat the water in the boiler and the

pipes (i.e. losses are relatively low), but the temperature of the flame and heat transfer process is much higher (above 1000°C) than the demand temperature of the space heating (around 60°C in the pipes and 20°C in the room). Hence the exergy supply mechanism is not well matched to the exergy demand of the system. Van Gool (1992) also proposed the concept of exergetic improvement potential, which is shown in Equation A21. The improvement potential includes parts that reflect the relative and absolute degree to which a process can be improved. The relative potential corresponds the first term in Equation A21, which is the relative exergy loss and destruction (cf. Equation A16 above) from and within the system respectively. The relative loss indicates the overall thermodynamic potential to improve a system. The absolute improvement potential is the second term in Equation A21, which relates to the improvement potential by attacking its entropy production or irreversibility. Rivero et al. (2004) also suggests incorporating a third, additive term in Equation A21 to reflect the environmental potential – that is, the potential to exploit the exergy in the effluents.

$$IP = (1 - \psi)(E_{in} - E_{out}) \quad \text{A21}$$

More recently the scope of analysis has been extended somewhat, and applied to whole energy systems. This was manifested in the appearance of several major texts on exergy analysis in the 1980s, published on both sides of the Atlantic (Ahern, 1980, Kotas, 1985, Moran, 1982, Szargut et al., 1988). Kotas et al. (1995) have also attempted to formalise the rapid development of the exergy method, by suggesting a conventional nomenclature. This was mainly inspired by the variety of approaches, terms and symbols in use at that time. It seems to have been in part due to the formation of a Working Party for Nomenclature, which assembled at the Workshop on Teaching Thermodynamics at Cambridge, UK, in 1984. It is not clear how widely their proposed convention has been adopted though.

A2.2.4 Thermoeconomics and exergoeconomics

Thermoeconomics is the general term given to the heterodox school of thought concerned with applying the principles of thermodynamics to the field of economics. It developed largely from the ideas of Georgescu-Roegen (section 2.1.3). Thermoeconomics might also be used more specifically to refer to a combination of energy analysis and economic analysis for an energy system. Exergoeconomics (also known as exergy costing) can be considered as a subset of thermoeconomics. It involves the combination of exergy analysis and economic analysis for an energy system, whereby costs are assigned to individual exergy flows. The crucial distinction between thermoeconomics in general and exergoeconomics in particular is that the latter is an integrated technique which uses thermodynamics and thermodynamic techniques at all stages in the process. Tsatsaronis (1984) coined the term exergoeconomics to avoid ambiguity in this context. Tsatsaronis (1984, 1990, 1993, 1996, 1999) has also been one of the chief proponents of the method. He points to Keenan as being responsible for the idea of coupling exergy and cost streams, and Benedictas having first applied the method in 1949 (Tsatsaronis, 1996).

Exergoeconomics seems to have been inspired by the needs of engineers and system designers to better understand the implications of exergetic degradation within energy systems. Carrying out an exergy analysis alone is useful for identifying the location and size of the exergy losses and destructions, but it does not in any way indicate a course of action to ameliorate them. In short, the descriptive nature of thermodynamics does not place any relative value on alternative options. Tsatsaronis (1999, p.94) asks the question: “and now that I know how much exergy is destroyed in each component of a system, what do I do?”. This is exacerbated by the fact that removing the component with the highest exergy destruction does not necessarily result in the greatest thermodynamic improvement. Thus an iterative approach is to be favoured in which the whole system is gradually optimised (*ibid.*). By determining the economic value of exergy flows, one can make more informed and influential decisions about actions to take as result of analyses.

The crucial foundation for the tool of exergoeconomics is the notion that exergy is the only rational basis for assigning costs. At first this seems like an exergy theory of value, but strictly speaking it is not because the methodology allows for non-exergy related costs also to be accounted for. Nevertheless, a large amount of data is generally required in order to determine the costs of input exergy streams. This is one of the limitations of this method, and perhaps one of the reasons for its limited applications in industry: it appears to be somewhat esoteric as a methodology, and has therefore been relatively confined to academia. The reasons for this are not clear, but around a decade ago, this technique was still a novelty in industry (Tsatsaronis, 1996).

A3 Results and data

A3.1 Chapter 6

Polymer	Company, site	Postcode	Capacity (kt/yr)	Estimated energy use (PJ/yr)
PP	N/A	N/A	800	2.71
LDPE	Basell, Carrington, Manchester	M31 4AJ	120	0.44
LDPE	Huntsman, Wilton	TS10 4YA	400	1.47
HDPE	N/A	N/A	460	1.69
LLDPE	N/A	N/A	300	0.70
S-PVC	Hydro polymers, Ayncliffe	DL5 6EA	120	0.29
S-PVC	European Vinyls Corp, Barry, S. Glamorgan	CF64 5RP	250	0.59
S-PVC	IneosChlor, Runcorn	WA7 4JE	105	0.25
SBR	Polimeri Europa, Grangemouth	FK3 9XE	110	1.60
E-SBR	Polimeri Europa, Southampton	SO45 3YY	90	0.47
HIPS	Nova Chemicals, Carrington, Manchester	M31 4TJ	110	0.15
HIPS	Atofina/Total, Stalybridge	SK15 1PY	130	0.31
VCM	IneosChlor Vinyls, Runcorn	WA7 4JE	300	1.51
PET	DU Pont SA/Sabancı Holdings	N/A	384	5.13
PET	Eastman Chemical, Workington, Cumbria	CA14 1LG	155	2.07
TOTAL				19.38

Table A2 – UK production capacity and total energy consumption for key polymers

Source: European Commission (2005d) and Chemical Week's *Product Focus* (various issues)

N/A – not available

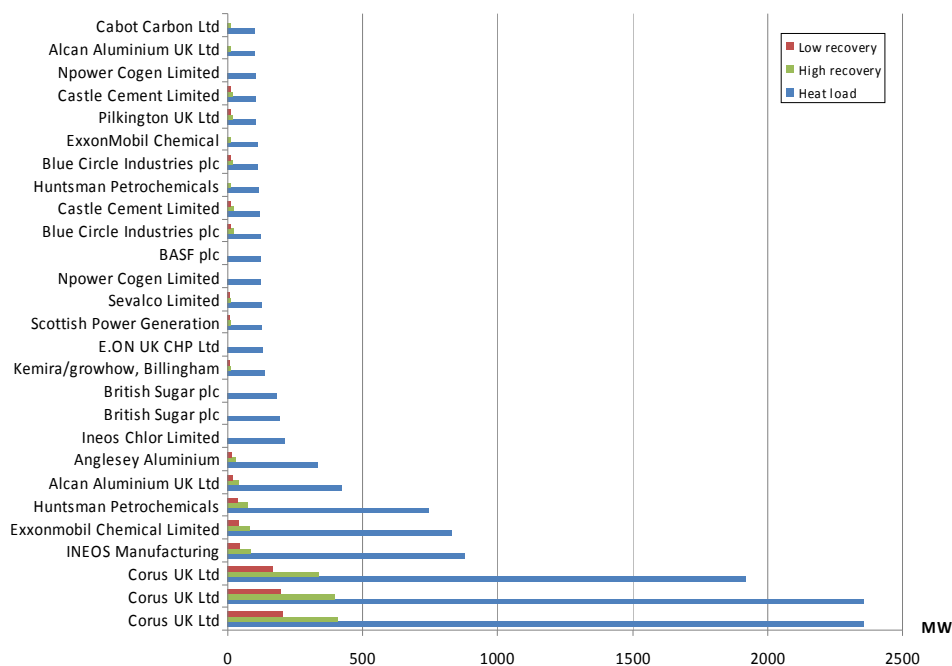


Figure A7 –All heat loads over 100MW by operator and estimated recovery potentials

Sector	Fuel split (% by energy)											Source (fuel split and temperatures)
	Combustion emissions fract.	Fuel to heat efficiency	Load factor	Natural gas	Gas oil	Fuel oil	Coal	Coke	Other (waste, biomass etc.)	Electricity	Total emissions factor (tC/TJ)	
Aluminium	N/A	1.0	0.95						0.10	0.90	22.00	European Commission, 2001b
Cement	0.33	0.9	0.95				0.58	0.18	0.11	0.13	27.37	Entec UK Ltd., 2006e
Ceramics_bricks	0.50	0.9	0.86	0.80		0.05				0.15	14.35	Enviros Consulting, 2006c
Chemicals_ammonia	N/A	0.8	0.85	0.90					0.05	0.05	14.41	European Commission, 2004c
Chemicals_carbon black	1.00	0.8	0.90	0.90					0.05	0.05	14.41	European Commission, 2005c
Chemicals_CHP	1.00	0.8	0.85	0.78			0.09		0.13		15.92	BERR, 2008c; National Grid, 2008
Chemicals_general	1.00	0.8	0.90	0.60		0.05			0.05	0.30	15.00	Enviros Consulting, 2002
Chemicals_steam crackers	N/A	0.8	0.70	0.90					0.05	0.05	14.41	Enviros Consulting, 2006a
Food and drink_boilers	1.00	0.8	0.80	0.66	0.02					0.32	14.14	DTI, 2007
Food and drink_breweries	1.00	0.8	0.80	0.76	0.01	0.02				0.21	14.21	Tighe, A., BBPA, pers. comm., April 2006
Food and drink_CHP	1.00	0.8	0.77	0.88	0.10	0.01	0.01				14.66	BERR, 2008c; National Grid, 2008
Food and drink_distilleries	1.00	0.8	0.80	0.76	0.08	0.04				0.12	14.73	DTI, 2007b
Food and drink_maltings	1.00	0.8	0.80	0.84	0.04					0.12	14.22	DTI, 2007b
Food and drink_sugar	1.00	0.8	0.80	0.95		0.01	0.03			0.01	14.35	DTI, 2007b
Glass_flat	0.70	0.9	0.85	0.69		0.30				0.01	15.87	Enviros Consulting, 2006d
Glass_container	0.70	0.9	0.85	0.62		0.32				0.06	16.10	Enviros Consulting, 2006d
Glass_other	0.70	0.9	0.70	0.60		0.35				0.05	16.28	Enviros Consulting, 2006d
Glass_CHP	1.00	0.8	0.85	1.00							13.99	3 10MW _e gas turbines; National Grid, 2008
Lime_LRK	0.40	0.9	0.95	0.03		0.01		0.81	0.14	0.01	25.19	European Commission, 2001a, 2007

Sector	Fuel split (% by energy)											Source (fuel split and temperatures)
	Combustion emissions fract.	Fuel to heat efficiency	Load factor	Natural gas	Gas oil	Fuel oil	Coal	Coke	Other (waste, biomass etc.)	Electricity	Total emissions factor (tC/TJ)	
Lime_PFRK	0.40	0.9	0.95	0.61		0.10	0.10	0.10	0.06	0.03	17.41	European Commission, 2001a, 2007
Lime_MFSK	0.40	0.9	0.95					0.99		0.01	26.22	European Commission, 2001a, 2007
Semiconductors_boilers	1.00	0.8	0.80	0.26	0.03	0.02				0.69	14.88	DTI, 2007b
Aerospace_CHP	1.00	0.8	0.80	0.77		0.23					15.42	BERR, 2008c; National Grid, 2008
Aerospace_boilers	1.00	0.8	0.80	0.57	0.08	0.02				0.33	14.78	DTI, 2007b
Other_CHP	1.00	0.8	0.80	0.99	0.01						14.04	BERR, 2008c; National Grid, 2008
Automotive_boilers	1.00	0.8	0.70	0.60	0.04		0.06			0.30	15.13	DTI, 2007b
Automotive_CHP	1.00	0.8	0.70	0.77		0.23					15.42	BERR, 2008c; National Grid, 2008
Gypsum	1.00	0.9	0.80	0.72						0.28	13.99	DTI, 2007b
Mineral/rock wool	0.70	0.9	0.85	0.80	0.07	0.07				0.06	14.83	DEFRA, 2007e; DTI, 2007b
Tobacco_boilers	1.00	0.8	0.80	0.46						0.54	13.99	DTI, 2007b
Munitions_boilers	1.00	0.8	0.80	0.54		0.06				0.40	14.61	DTI, 2007b
Textiles_boilers	1.00	0.8	0.80	0.41	0.26	0.10				0.23	16.51	DTI, 2007b
Tyres_boilers	1.00	0.8	0.80	0.10	0.52	0.28				0.10	18.86	DTI, 2007b
Pulp and paper_boilers	1.00	0.8	0.90	0.51			0.07			0.42	15.18	DTI, 2007b
Pulp and paper_CHP	1.00	0.8	0.95	0.94	0.01		0.04		0.01		14.52	BERR, 2008c; National Grid, 2008

Table A3 – Specification of individual sectors: process emissions, fuel split and emissions factors
N/A – not applicable as sector is based on SEC methodology

Subsector	Total primary energy	Total fuel and electricity	Net grid electricity	Electricity	Other	Coke oven gas	Coke	Coal	Fuel oil	Gas oil	Natural gas
Aluminium_primary Total	55.94	25.93	23.33	23.33	2.59	0.00	0.00	0.00	0.00	0.00	0.00
Cement_dry Total	43.81	36.14	4.70	4.70	3.98	0.00	6.51	20.96	0.00	0.00	0.00
Cement_wet Total	9.27	7.65	0.99	0.99	0.84	0.00	1.38	4.43	0.00	0.00	0.00
Ceramics_bricks Total	24.01	19.29	2.89	2.89	0.00	0.00	0.00	0.00	0.96	0.00	15.43
Chemicals_ammonia Total	14.31	13.23	0.66	0.66	0.66	0.00	0.00	0.00	0.00	0.00	11.91
Chemicals_carbon black Total	8.19	7.57	0.38	0.38	0.38	0.00	0.00	0.00	0.00	0.00	6.81
Chemicals_CHP Total	70.11	70.11	-15.23	0.00	9.11	0.00	0.00	6.31	0.00	0.00	54.69
Chemicals_general Total	60.70	40.75	12.23	12.23	2.04	0.00	0.00	0.00	2.04	0.00	24.45
Chemicals_steam cracker Total	76.82	71.03	2.13	3.55	3.55	0.00	0.00	0.00	0.00	0.00	63.92
Food and drink_boilers Total	52.33	34.38	9.63	11.00	0.00	0.00	0.00	0.00	0.00	0.69	22.69
Food and drink_breweries Total	10.49	7.82	1.61	1.64	0.00	0.00	0.00	0.00	0.16	0.08	5.94
Food and drink_CHP Total	34.55	34.55	-8.88	0.00	0.00	0.00	0.00	0.35	0.35	3.45	30.40
Food and drink_distilleries Total	4.82	4.03	0.26	0.48	0.00	0.00	0.00	0.00	0.16	0.32	3.06
Food and drink_maltings Total	1.39	1.16	0.14	0.14	0.00	0.00	0.00	0.00	0.00	0.05	0.98
Food and drink_sugar beet Total	0.36	0.35	-0.40	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.33
Food and drink_sugar cane	0.40	0.39	-0.35	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.37
Glass_CHP Total	0.66	0.66	-0.61	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.66
Glass_container Total	16.26	14.81	0.89	0.89	0.00	0.00	0.00	0.00	4.74	0.00	9.18
Glass_flat Total	9.39	9.23	0.09	0.09	0.00	0.00	0.00	0.00	2.77	0.00	6.37
Glass_other Total	1.09	1.01	0.05	0.05	0.00	0.00	0.00	0.00	0.35	0.00	0.61
Lime_LRK Total	5.66	5.57	0.06	0.06	0.78	0.00	4.51	0.00	0.06	0.00	0.17
Lime_MFSK Total	3.29	3.23	0.03	0.03	0.00	0.00	3.20	0.00	0.00	0.00	0.00
Lime_PFRK Total	7.72	7.36	0.22	0.22	0.44	0.00	0.74	0.74	0.74	0.00	4.49

Subsector	Total primary energy	Total fuel and electricity	Net grid electricity	Electricity	Other	Coke oven gas	Coke	Coal	Fuel oil	Gas oil	Natural gas
Gypsum Total	17.28	11.86	3.32	3.32	0.00	0.00	0.00	0.00	0.00	0.00	8.54
Mineral/rock wool Total	3.14	2.86	0.17	0.17	0.00	0.00	0.00	0.00	0.20	0.20	2.29
Aerospace_boilers Total	13.43	8.73	2.54	2.88	0.00	0.00	0.00	0.00	0.17	0.70	4.97
Aerospace_CHP Total	3.79	3.79	-2.28	0.00	0.00	0.00	0.00	0.00	0.87	0.00	2.92
Automotive_boilers Total	16.20	10.87	3.04	3.26	0.00	0.00	0.00	0.65	0.00	0.43	6.52
Automotive_CHP Total	2.07	2.07	-0.35	0.00	0.00	0.00	0.00	0.00	0.48	0.00	1.59
Other_CHP Total	2.74	2.74	-0.42	0.00	0.00	0.00	0.00	0.00	0.00	0.03	2.72
Semiconductors_boilers Total	1.95	0.92	0.63	0.63	0.00	0.00	0.00	0.00	0.02	0.03	0.24
Munitions_boilers Total	4.89	2.96	1.18	1.18	0.00	0.00	0.00	0.00	0.18	0.00	1.60
Textiles_boilers Total	0.74	0.54	0.12	0.12	0.00	0.00	0.00	0.00	0.05	0.14	0.22
Tobacco_boilers Total	1.67	0.89	0.48	0.48	0.00	0.00	0.00	0.00	0.00	0.00	0.41
Tyres_boilers Total	1.94	1.67	0.17	0.17	0.00	0.00	0.00	0.00	0.47	0.87	0.17
Pulp and paper_boilers Total	49.48	29.36	10.68	12.33	0.00	0.00	0.00	2.06	0.00	0.00	14.97
Pulp and paper_CHP Total	48.81	48.81	-8.27	0.00	0.49	0.00	0.00	1.95	0.00	0.49	45.88
Iron and Steel_coke ovens Total	12.06	11.45	0.23	0.23	0.57	10.65	0.00	0.00	0.00	0.00	0.00
Iron and Steel_sinter plants	21.06	19.07	1.33	1.33	0.00	1.53	16.21	0.00	0.00	0.00	0.00
Iron and Steel_blast furnace	157.06	155.00	1.55	1.55	37.20	0.00	102.30	13.95	0.00	0.00	0.00
Iron and Steel_BOF Total	19.15	17.60	6.87	6.87	7.39	0.00	0.00	0.00	0.00	0.00	3.34
Iron and Steel_CC Total	9.37	3.56	3.21	3.21	0.36	0.00	0.00	0.00	0.00	0.00	0.00
Iron and Steel_mills Total	52.82	33.39	11.69	11.69	21.71	0.00	0.00	0.00	0.00	0.00	0.00
Iron and Steel_EAF Total	22.85	10.77	7.54	7.54	0.00	0.00	0.00	1.08	0.00	0.00	2.15
Iron and Steel Total	294.37	250.85	32.41	32.41	67.23	12.18	118.50	15.03	0.00	0.00	5.50
Grand total	1268.41	1046.01	110.67	152.73	159.32	24.35	253.34	67.53	14.77	7.47	366.51

Table A4 – Total sector energy consumption by fuel (PJ)

A3.2 Chapter 7

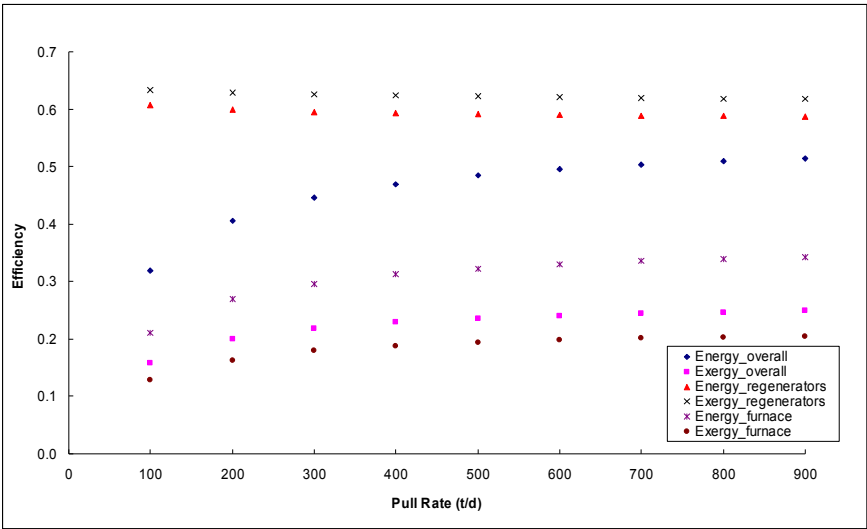


Figure A8 – Effect of pull rate on furnace efficiencies

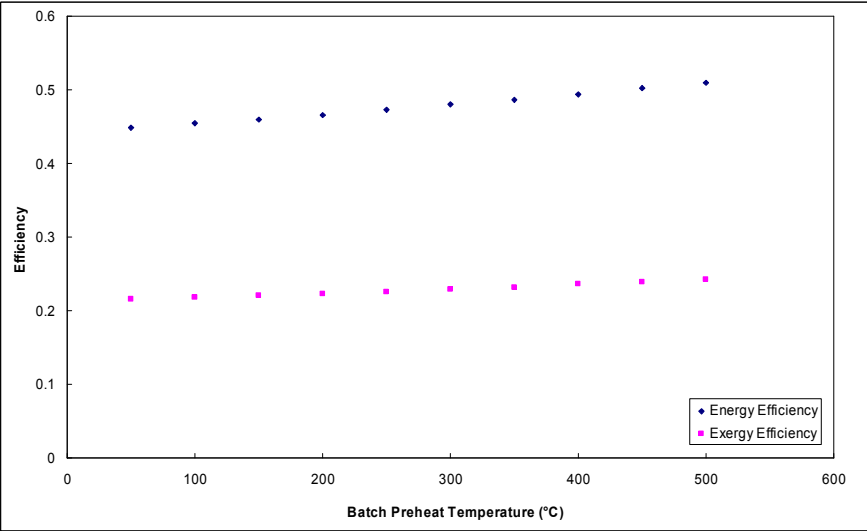


Figure A9 – Effect of batch preheating on overall efficiencies

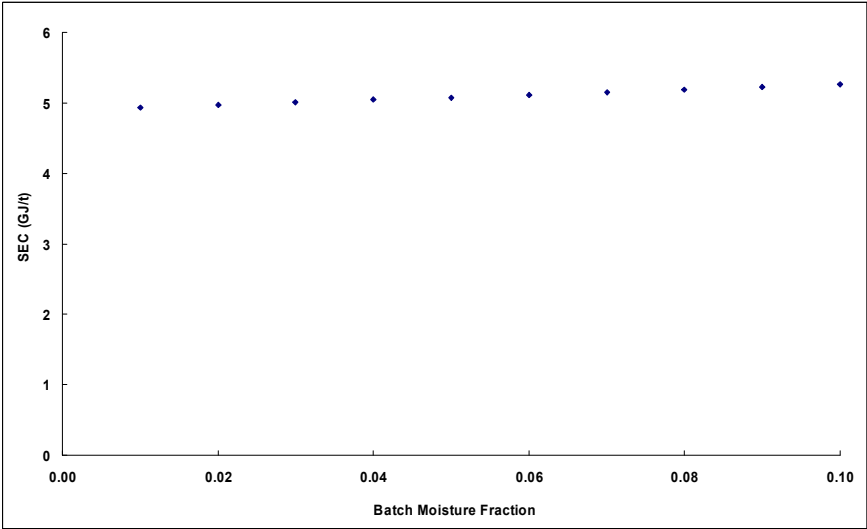


Figure A10 – SEC against moisture fraction

A3.3 Chapter 8

A3.3.1 Pulp and paper process diagram

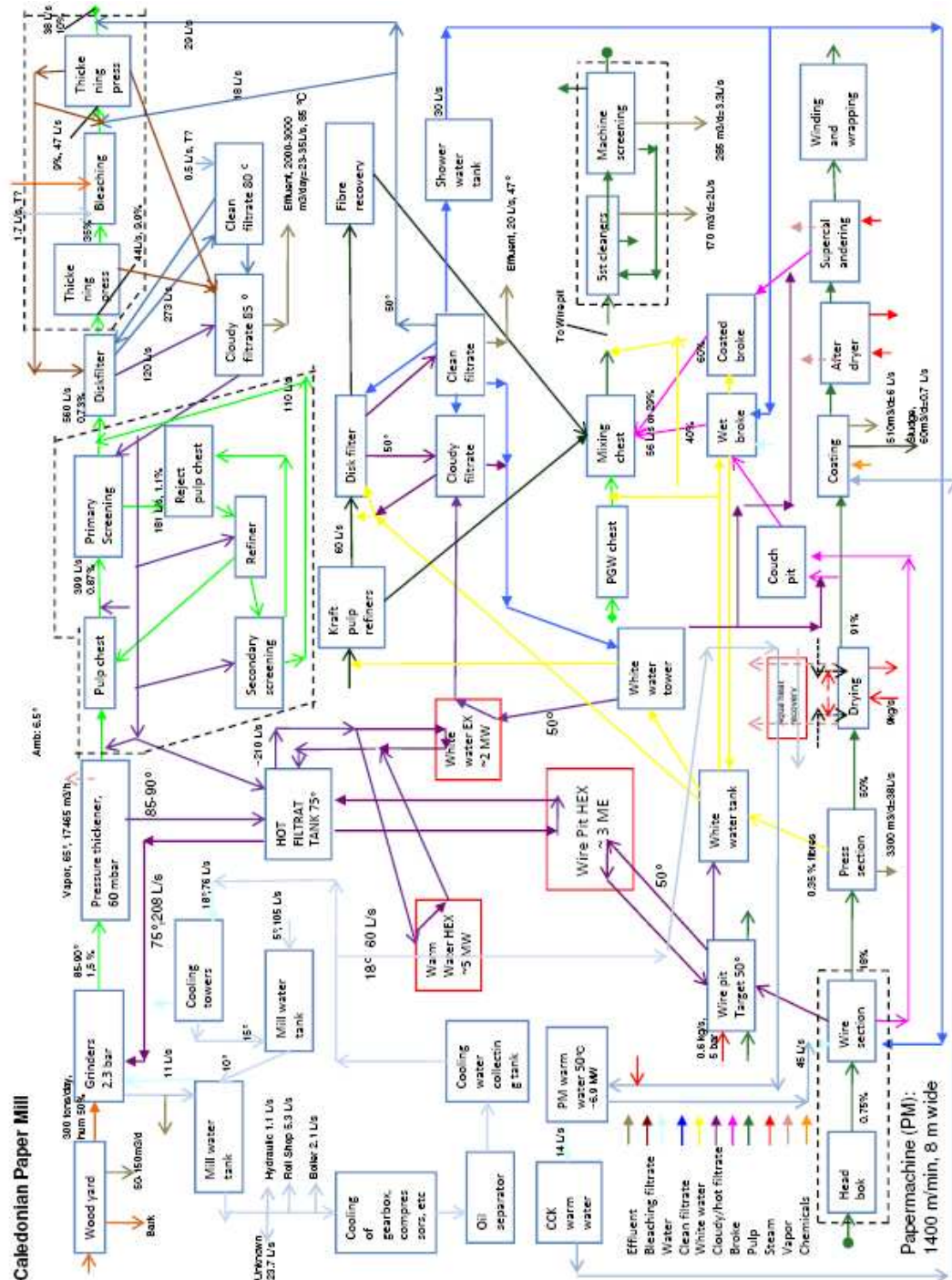


Figure A11 – Sketch of pulp and paper process at the mill. The process continues after the Bleaching Thickening Press in PGW chest. The process continues after machine screening in the Paper Machine Head Box.

A3.3.2 Grinders data

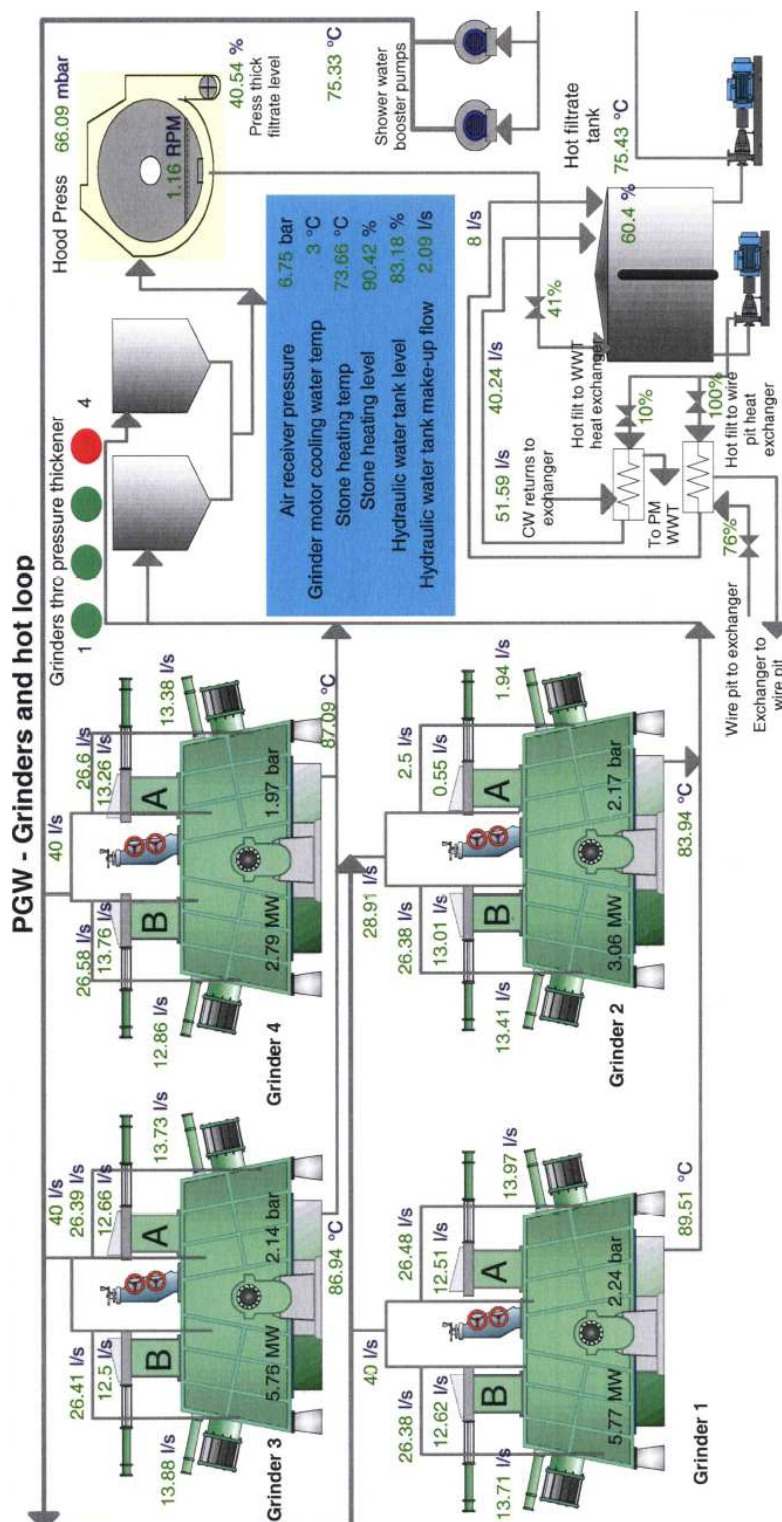


Figure A12 – Instantaneous measurements from online data system of grinders and hot loop.

A3.3.3 Overview of effluent system

PGW cloudy filtrate overflow is estimated to 2000-3000 m³/day.

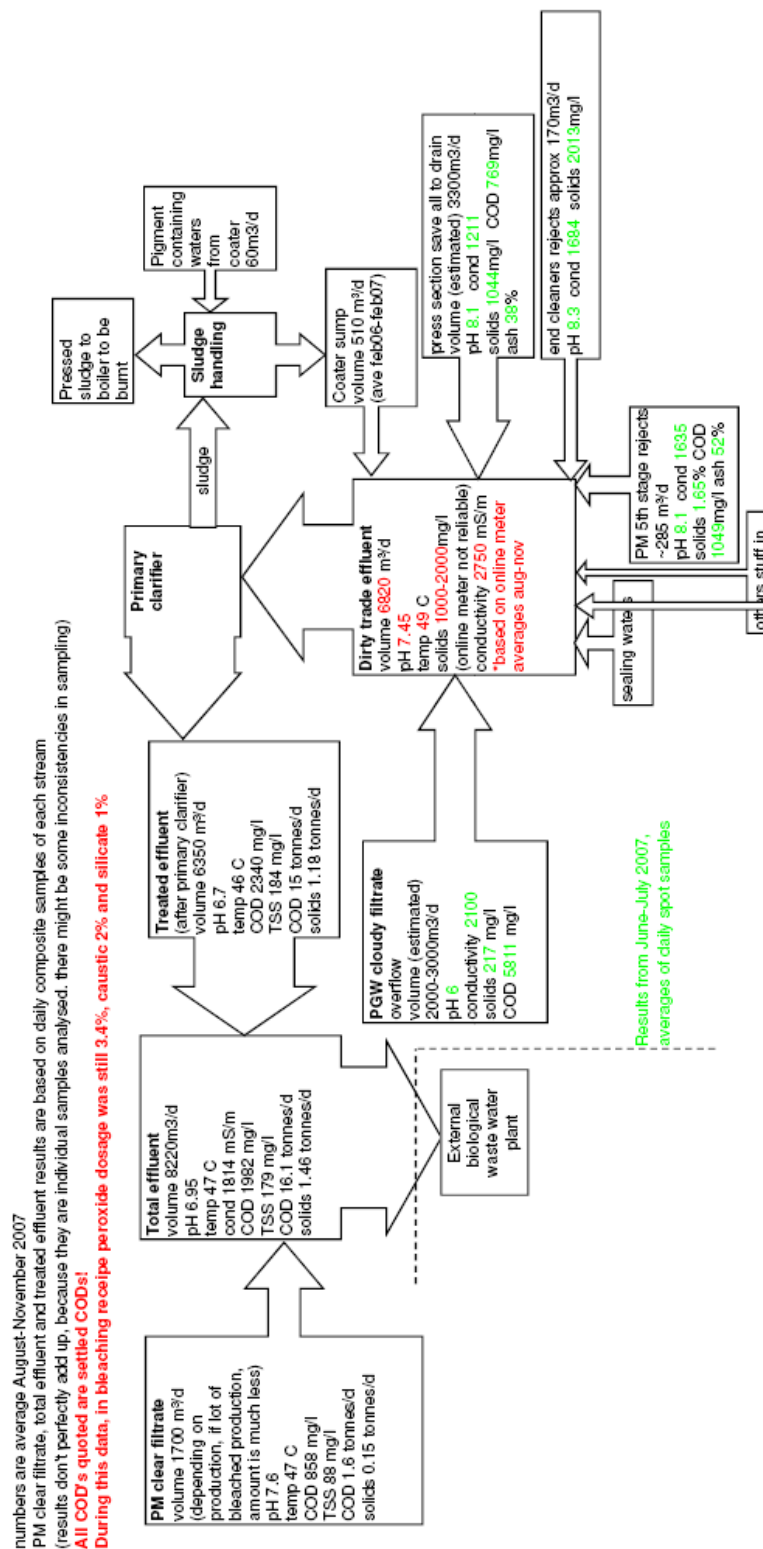


Figure A13 – Overview of effluent system

A3.3.4 Data for the heating banks and AHR

Vessel position: 20 % = 5 L/s per bank

	Bank 1		Bank 2		Bank 3		Bank 4		Bank 5		Bank 6	
	T _{in}	T _{out}	T _{in}	T _{out}	T _{in}	T _{out}	T _{in}	T _{out}	T _{in}	T _{out}	T _{in}	T _{out}
14:00	35.7	53.3	35.4	53.4	35.1	51.6	35.5	52.6	35.3	51.5	34.9	50.6
14:30	36.7	53.2	36.0	53.4	35.2	51.9	36.3	53.1	36.4	51.9	35.7	51.6
14:45	38.6	52.7	37.9	52.9	37.4	51.1	37.8	52.6	37.3	51.4	37.2	51.1
15:00	35.9	53.4	36.2	53.5	35.8	51.9	36.0	52.8	36.0	51.9	36.0	51.4
15:15	37.9	52.3	37.6	52.4	37.7	51.7	36.8	52.2	37.5	51.4	37.1	51.3

Table A6 – Measured inlet and outlet temperatures in °C of Mill Warm Water

Vessel position: 100 % = 10 L/s per bank

	Bank 1		Bank 2		Bank 3		Bank 4		Bank 5		Bank 6	
	T _{in}	T _{out}	T _{in}	T _{out}	T _{in}	T _{out}	T _{in}	T _{out}	T _{in}	T _{out}	T _{in}	T _{out}
14:00	34.7	47.3	31.7	45.9	34.2	46.4	32.1	47.3	33.4	45.6	31.4	45.9
14:30	34.9	48.1	35.3	46.8	35.4	46.9	36.4	48.1	35.8	46.3	32.8	46.4
14:45	27.3	45.9	29.2	43.2	28.6	45.1	26.2	44.8	27.1	42.2	26.3	42.8
15:00	36.1	47.9	35.3	46.9	36.3	46.9	36.7	47.9	36.4	46.4	37.3	46.8
15:15	27.1	45.6	28.9	42.8	27.9	44.8	26.0	44.6	26.9	42.1	25.9	42.8

Table A7 – Measured inlet and outlet temperatures in °C of Mill Heating Water

Outlet air temperature [°C]	\dot{Q}_{total} [kW]	$\dot{Q}_{\text{d.a.}}$ [kW]	f_{cond}
20	13607	2394	5.68
25	12566	2151	5.84
30	11311	1908	5.93
35	9780	1665	5.88
40	7893	1422	5.55
45	5538	1179	4.70
50	2561	936	2.74
55	874	693	1.26
60	567	450	1.26
69.25	0	0	0

Table A8 – Specific condensation factor for average humidity ratio

A3.3.5 Calculation of the heat transfer coefficient on the cold side

The heat transfer coefficient on the cold side is determined from the Nusselt number, Nu,

$$\text{Nu} = 0.023 \times \text{Re}_{d_i}^{\frac{4}{5}} \times \text{Pr}^{0.4}$$

$$h_c = \frac{k_c}{d_i} \times \text{Nu}$$

where k_c is the thermal conductivity and Pr is the Prandtl number. The Reynolds number is calculated on basis of mean velocity, U_m .

$$U_m = \frac{\dot{m}_t}{\rho \times A_i} = \frac{4 \times (\dot{m}_{total} / N_t)}{\rho \times \pi \times d_i^2}$$

$$Re_{d_i} = \frac{\rho \times U_m \times d_i}{\mu} = \frac{4 \times (\dot{m}_{total} / N_t)}{\pi \times d_i \times \mu}$$

The pressure drop in the tubes can be found from

$$\Delta p_t = 4 \times f \times \frac{L \times N_p}{d_i} \times \rho \times \frac{U_m^2}{2}$$

$$\Delta p_r = 4 \times N_p \times \frac{\rho \times U_m^2}{2}$$

$$\Delta p_{total} = \Delta p_t + \Delta p_r = \left(4f \frac{L \times N_p}{d_i} + 4N_p \right) \frac{\rho \times U_m^2}{2}$$

where Δp_r represents losses due to bending of tubes in the N_p number of tube passes according to (Kakac & Liu, 2002). The friction factor, f , is estimated by Kakac & Lui (2002) for turbulent flow in hydraulic smooth tubes ($Re = \rho U_m d_i / \mu > 10^4$):

$$f = (1.58 \times \ln(Re) - 3.28)^{-2}.$$

Parameter	Value	Source:
h_h	$\approx 50 \text{ W/m}^2\text{K}$	Sivill et al., 2005
λ	60 W/mK	Incropera & DeWitt, 1996 (stainless steel)
F	1	Incropera & DeWitt, 1996 Figure 11.13, "Correction factor for single-pass, cross-flow heat exchanger"
Pr	7.56	Incropera & DeWitt, 1996 Table A.6 (T = 290 K)
k_c	0.598 WmK	
ρ	1000 kg/m^3	
μ	$1080 \cdot 10^{-6} \text{ Ns/m}^2$	

Table A9 – The values assumed for use in dimensioning the overall heat transfer coefficient.

The DNA simulation model in Appendix A3.4.10 was used to find the temperature of the air through the AHR unit for four different time measurements (14:00, 14:30, 15:00 and 15:15). The reason for only employing these four values was that the other measurement, at 14:45, is almost identical to the one at 15:15. T_{11} to T_{17} refers to the temperature in the nodes in the DNA model. The following values were measured in Table A6 and Table A7.

		14:00	14:30	15:00	15:15
m_dot_air_i	[kg/s]	56.0	56.0	56.0	56.0
Average T _i , Mill Water (T ₁₃)	[°C]	35.3	36.1	36.1	37.5
Average T _o , Mill Water (T ₁₄)	[°C]	52.2	51.5	52.5	51.9
m_dot_Mill Water	[kg/s]	30.0	30.0	30.0	30.0
Average T _i , Warm Water (T ₁₆)	[°C]	32.9	35.1	36.5	27.0
Average T _o , Warm Water (T ₁₇)	[°C]	46.4	47.1	47.3	43.7
m_dot_Warm Water	[kg/s]	60.0	60.0	60.0	60.0
T _{roof ventilation} (T ₁₅) measured	[°C]	47.7	47.3	47.8	45.5

Table A10 – Average measurements from heating bank 1-6 in Mill Heating Water HEN and Warm Water HEN and the measured roof ventilation temperature.

These values are used as input to the simulation model, which gives the output as shown in Table A11.

		14:00	14:30	15:00	15:15
T ₁₁	[°C]	68.2	68.2	68.2	68.4
T ₁₂	[°C]	53.6	53.9	53.7	54.1
T ₁₅	[°C]	46.6	47.5	47.8	45.6
Humidity ratio, w ₁₁	[kg _{water} /kg _{air}]	0.15	0.15	0.15	0.15
Humidity ratio, w ₁₂	[kg _{water} /kg _{air}]	0.13	0.14	0.14	0.14

Table A11 – The temperature and humidity ratio through AHR according to DNA model

The measured and calculated outlet air temperatures (T₁₅) are almost identical for all measurements except the one at 1400. At this time there is a deviation between measured and calculated temperatures of around 2%. The minimum installed heat transfer area is now estimated based on previous equations for heat transfer from dry air, $\dot{Q}_{d.a.}$, the specific condensation factor, f_{cond} and logarithmic mean temperature:

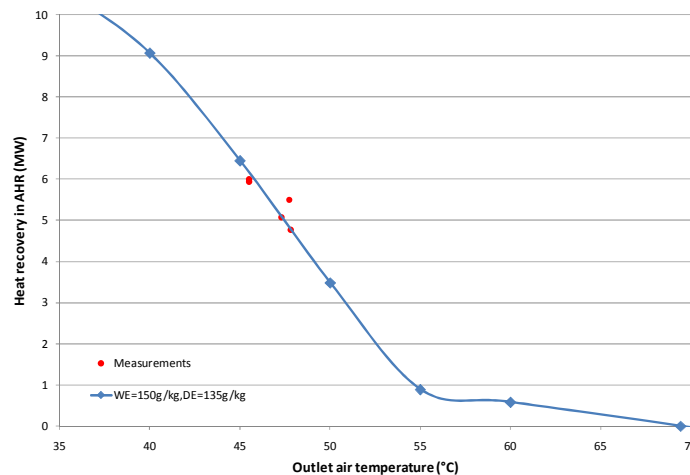


Figure A14 – Heat recovery as a function of outlet air temperature. A good correlation is found between measurements and humidity ratio of WE = 150 g/kg and DE = 135 g/kg.

A3.3.6 Specific heat capacity for humid air

The specific heat capacity of humid air for the average humidity ratio (WE = 140 g/kg, DE = 130 g/kg) is calculated in the interval i (changes in the total mass flow of air due to condensation are ignored):

$$c_{p,i} = \frac{\dot{Q}_i - \dot{Q}_{i-1}}{(T_i - T_{i-1}) \times \dot{m}_{\text{air,total}}}$$

T [°C]	$Q_{\text{total}} = Q_{\text{AHR}} + Q_{\text{pre-heat}}$ [kW]	c_p [kJ]/(kgK)]
20	14211	3.72
25	13170	4.48
30	11915	5.47
35	10385	6.74
40	8497	8.41
45	6142	10.64
50	3165	6.03
55	1478	1.09
60	1171	1.10
69.25	604	1.23
78	0	

Table A12 – Specific Heat Value of humid air in different temperature intervals

A3.3.7 Biomass boiler

The biomass boiler model in DNA consists of two components: a burner and a heat sink, as shown in Figure A15.

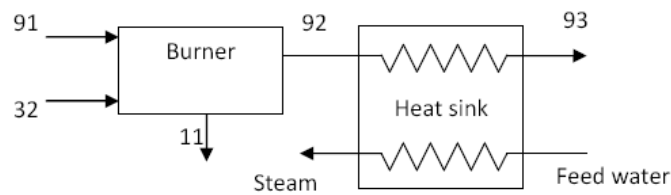


Figure A15 – Schematic of biomass boiler as represented in DNA

The combustion process in the burner is calculated for a constant excess heat ratio of $\lambda = 1.23$ and pressure ratio of 0.9. The burner is assumed to be adiabatic. The heat transfer in the boiler is constant at 89.57MW and the outlet temperature of the flue gas to the stack is 145°C.

A3.3.8 Thermodynamic analysis of biomass CHP – Rankine process

The steam cycle is modeled in DNA based on data from the manufacture, Pöyry. The steam (Rankine) cycle has a maximum pressure and temperature of 90bar and 509°C, respectively. The thermal heat effect to the steam cycle is 89.6MW. There are four steam extractions in the turbine; two are used for feed water preheating (11.75bar and 1.12bar) and two supply the steam demand in the paper mill at 10bar and 5bar. The electricity production is approximately 26MW and the process heat supply is approximately 26MW at 5bar steam pressure and 2.4MW at 10bar steam pressure. The production of electricity is not enough to cover the demand in the pulp and paper mill.

The steam consumption in the paper mill determines the mass flow through the medium and low-pressure turbine. Increased mass flow through the turbine leads to higher electricity production. However, a small increase in steam extraction at 1.12bar is needed to achieve same temperature after the feed water preheating. The correlation between steam extraction at 5bar and change in electricity consumption is shown in Figure A19. The isentropic efficiency of the turbine is assumed to be constant. The correlation is used to determine the cost of steam consumption in equivalent electricity production. Based on the lower heating value and percentage of thermal heat effect the mass flow rate of biomass is calculated in Table A13.

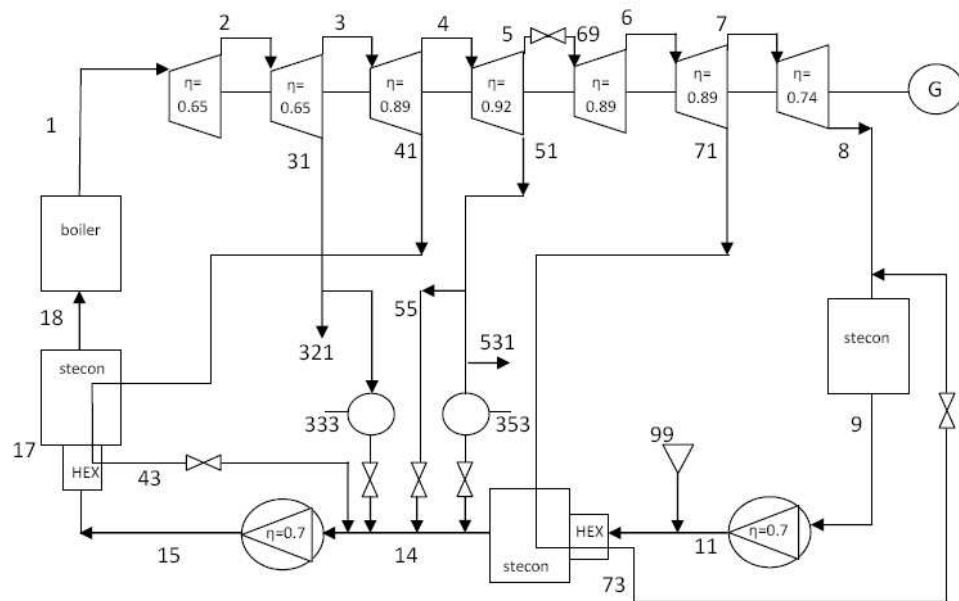


Figure A17 – The steam cycle with isentropic efficiencies for turbines and pumps

The Rankine process is shown in Figure A17 based on data provided by the manufacture, Pöyry. The mass flow through the medium and low pressure turbine will change when the 5bar steam consumption is changed (node 51). Thus, the steam extraction in node 71 is varied to maintain constant temperature after the first preheating. The steam quality is set to $x = 0$ after the second condensate pump to simulate the de-aerator. This will determine the steam extraction in node 55. The consumption of 10bar and 5bar direct steam injection is represented by nodes 321 and 531 respectively. This requires new fresh water supply in node 99. The

consumption of 10bar and 5bar steam in the paper mill is modelled by two heat sinks, 333 and 353 respectively.

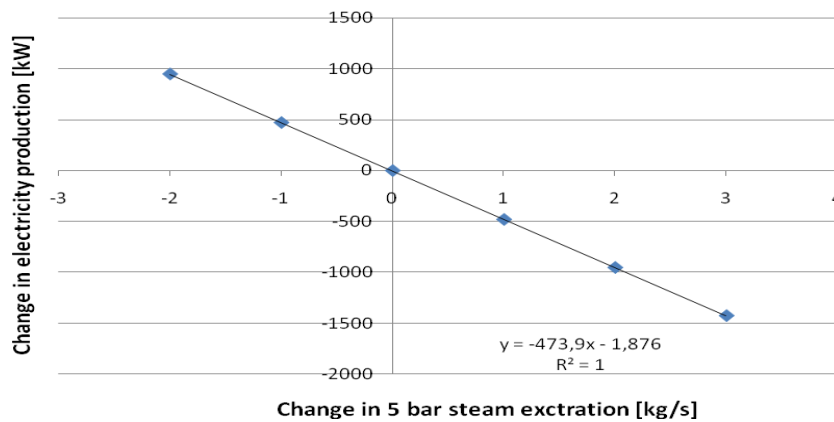


Figure A19 – Change in electricity production as function of 5 bar steam extraction

	Moisture content (weight %)	LHV (GJ/t)	% of thermal heat effect	Mass flow (kg/s)
Logs of round wood	46	8.2	38.0	4.6
Wood chips of Sawmill residues	55	9.0	17.1	1.9
Forest residual plus stump	60	8.8	23.3	2.6
Demolition wood	20	14.7	15.0	1.0
Effluent Sludge	50	3.5	2.0	0.6
Bark	55	6.0	4.6	0.8
Total				11.8

Table A13 – Biomass utilisation in the CHP plant (Mott MacDonald, 2008)

A3.3.9 DNA model

The model uses four condensing heat exchangers and a mixer to simulate the heat recovery from humid air in the air pre-heaters and AHR. The model is shown in Figure A21. The condensing heat exchanger (CHX) component in DNA, called gascool, calculates the sensible and latent heat transfer based on the temperatures of the hot and cold stream or vice versa, given that the humidity ratio of inlet air is defined. The CHX is assumed to be adiabatic and the condensate assumed to have the same temperature as the outlet air. The model determines the temperature and humidity ratio after the mixer. The heat transfer in the air pre-heaters is constant at approximately 200kW and 400kW for wet end and dry end, respectively.

When the model is used to estimate the humidity ratio as function of outlet temperature, gascoolC is removed and the outlet temperature is used as additional condition. The heat recovery is found via the mass flow and enthalpy change in the cold stream. When the model is used to estimate the temperature through AHR, the mass flow and inlet and outlet temperature of the cold streams are defined as additional conditions, and the temperature T_{12} and T_{15} is output from the model. The calculated roof ventilation temperature is compared to the measured to validate the results.

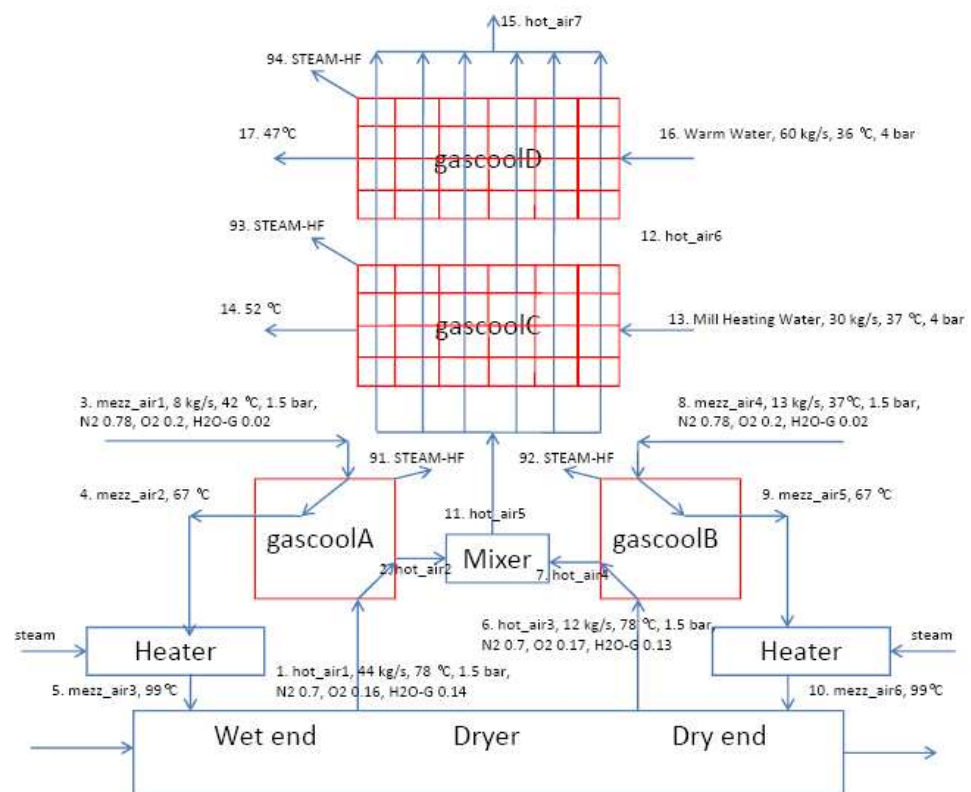


Figure A21 – DNA components in simulation model of heat recovery in the paper machine